MODELS FOR TMDL APPLICATION IN TEXAS WATERCOURSES:

SCREENING AND MODEL REVIEW

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1. INTRODUCTION

The concept of Total Maximum Daily Load (TMDL), as expressed in Section 303(d) of the Clean Water Act, is a generalization and formalization of the older concept of wasteload assimilative capacity, *viz*. the upper limit on the discharge of a wasteload into a receiving watercourse so that the resulting concentration of some indicator parameter carried by the waste stream remains within a predetermined limit. Generally, the predetermined limit was a stream standard, and the assimilative capacity was established under a set of critical conditions, typically extreme low flows and high temperatures. An associated concept was that of wasteload allocation, in which the assimilative capacity, once determined, was apportioned among several waste dischargers. The TMDL includes not only point source discharges, but also natural sources of the pollutant and so-called nonpoint sources that arise from the watershed (EPA, 1991) or environs of the watercourse.

The TMDL is a much more complex determination, in part because it entails quantifying the concentrations of water quality parameters under a range of hydrometeorological conditions that are perhaps changing dynamically in time, and in part because it expands the geographical domain of the problem to the tributary network and watershed of the watercourse. Because of this complexity, the use of mathematical models of the watercourse in question is mandatory in the TMDL process.

The technical complexity of the TMDL determination is rendered even greater because of the geographical and hydrometeorological characteristics of Texas, because of the variety of watercourses occurring in the state for which TMDL's are potentially required. A review of the current 303(d) list indicates that a TMDL will be required of almost every example of Texas watercourse, including streams, rivers, reservoirs and estuaries, of various spatial dimensions and hydrographic features. In order to address TMDL determination in Texas, clearly models for a wide array of watercourses must be available to the State, which moreover must be suitable for accurately depicting its variable hydroclimatology and terrain, and the concomitant effects on the watercourse. Because the TMDL modeling must incorporate nonpoint source loadings, there needs to be a means of coupling the model to the watershed.

The objective of this study is stated as follows:

> To conduct an independent assessment of existing watershed-scale nonpoint source loading models and instream water quality models appropriate to Texas environments, with a focus on the relative ease of integration with an ArcView-based geospatial Graphical User Interface (GUI).

The purpose of this report, therefore, is to provide a review and critical evaluation of watercourse models with respect to their potential for application to aquatic systems of Texas for which Total Maximum Daily Load (TMDL) determinations are required. This review addresses both watershed-scale nonpoint-source loading models and instream water-quality models appropriate to Texas environments, with a focus on the relative ease of integration with an ArcView-based geospatial Graphical User Interface (GUI).

Specific objectives of the review were:

(1) Compile list of candidate models.

(2) Obtain detailed information about the computer implementation of each model.

(3) Delineate capabilities and limitations of each model, with special emphasis on requirements of Texas watercourses.

(4) Determine (where appropriate) the capability of each model for incorporation into Arc-View environment.

(5) Formulate a "short list" of recommended models for the TNRCC.

The results of this work are presented in two separate documents with differing strategies. The present report provides a model-by-model summary, cataloging the properties and capabilities of each of the models reviewed. A companion report (Ward and Benaman, 1999) presents a narrative summary of the model review, attempting to discuss the Texas requirements within a broader context of modeling strategy and philosophy.

The preliminary list, Objective (1) above, was combined from suggestions of the staffs of TNRCC and CRWR. In the early stages of the literature review, other models were added to the list if they seemed appropriate for at least preliminary consideration. In order to limit the scope of the review to ensure its completion within the limited resources for the project, a procedure of successive screening was applied to the list of candidate models. This screening was exclusionary, seeking to eliminate candidate models as early in the screening sequence as possible, so as to minimize the effort invested in review. Therefore, the first level of screening was fairly coarse and focused on crucial attributes that useful models were required to possess, such as being implemented in a transportable, modifiable computer code that is readily available and non-proprietary. The successive screening levels became increasingly detailed and technical as the review proceeded, so that the effort of detailed review was limited to a minority of those on the list of candidates. Details of this screening process are given in the next section.

Constraints of time and budget dictated that this review rely upon sources in the technical literature and on discussions with recent users of the models under review. In this study, we did not acquire copies of model software and subject these models to independent evaluation, though such operational tests are recommended for the list of models that emerged as viable candidates for Texas TMDL application.

Several reviews of watercourse modeling software have appeared recently, to which the reader is referred who may desire a much more extensive listing of various watercourse models. These reviews generally are not critical, nor are they specific to the Texas situation. Singh (1995) is a useful summary of the features and operation of nearly 30 catchment models, including (in a companion CD) executables of model code or of model demonstrations (for proprietary models). The model reviews in Singh (1995) are authored mainly by the principal developers of the models. Shoemaker et al. (1997) is a catalog of aquatic models specifically identified as potentially useful in the TMDL process. Many of these transcend the domain of modeling of physico-chemical parameters in surface watercourses, which is the subject of the present study, addressing vadose-zone or groundwater models, toxicological or biological responses, or including risk-evaluation protocols.

In contrast to these and similar surveys, the present study was not intended to be a comprehensive literature review of each model, but rather a review adequate for supporting a decision of including or excluding such models for use in Texas. This was, however, a *critical* review. In addition to summarizing the features and capabilities of each model, we attempt to document limitations in model formulation, range of application and software performance, and technical acceptance, where these might circumscribe or hamper utility of the model in application to the Texas environment.

2. MODEL SCREENING

The constraints on time and budget under which this study was prosecuted required a specific focus on the expeditious formulation of a list of candidate TMDL models for Texas. In order to bound the scope of the review, it was necessary to establish screening criteria, in order to efficiently address models that have the potential to be (in order of priority):

(1) suitable for incorporation into a TMDL-determination process
(2) applicable to the surface-water environments of Texas
(3) capable of taking advantage of GIS technology for both input development and display of results

by eliminating candidates that clearly do not satisfy at least one of these requirements. In addition to these criteria of "utility," we also required that a candidate model have an adequate level of technical acceptability and economical viability. The former includes a history of satisfactory validation on watercourses similar to those encountered in Texas, as well as a history of satisfactory application of the computer codes involved. The latter refers to issues of acquisition and licensing of the code, the portability of the code to various platforms, and the ease of use by a new user. The intended users of models for TMDL determination in Texas are not expected to be model developers, and the TMDL process should not include computer programming. Therefore, the extent to which the model code has been designed for users without requiring intimate knowledge of the code is an important feature for this review. This can be difficult to assess, because one must distinguish between the complexity of a problem and the complexity of a model. There is a limit to which a model can simplify the problem set-up without sacrificing accuracy. On the other hand, the structure of the computer code should not compound complexity. A fairly trustworthy guide to the ease of use of a model is the massed experience of past users.

The evaluation procedure was preceded by the formulation of objective criteria to be applied in sequential tiers, thereby successively preening the field of candidates. This limited the number of candidate models for which detailed evaluations were necessary, and thereby maximized productivity from the resources of the project. It is important to note once again that this project is not a comprehensive review of models (which would far exceed the resources of the project), but is a review specific to the above three requirements. This qualification notwithstanding, this review addresses, at varying levels of detail:

physico-chemical model formulation,
solution numerics and discretization strategy,
coding and machine requirements, and
user accessibility.

2.1 Screening Level 1 Criteria

The purpose of Level-1 Criteria is to eliminate from further consideration candidate models that are "obviously" inappropriate for the Texas Natural Resource Conservation Commission (TNRCC) TMDL process. Level-1 Criteria were applied to both watershed and watercourse models. At this stage, these criteria were to be applied from an exclusionary viewpoint, to eliminate models from further consideration based on rather robust desiderata, summarized as follows:

(2-1) Stated physical system(s) for which model is applicable. These systems should be representative of Texas hydrological systems and Texas hydroclimates, as delineated below.

(2-1.1) For a watershed model, general nature of terrain and physiography addressed by model should include capability to depict at least one of:

- low-relief, semi-arid to subhumid basins
- basins dominated by fluvial drainageways
- substantially altered hydrology due to storage and conveyance systems
- substantially altered hydrology due to urbanization.

(2-1.2) Streams capable of representation by the model should include flashy and low-baseflow rivers and tributaries, dominated by fluvial-type bathymetry.

(2-1.3) If the model addresses lakes, it should include applicability to run-of-the-river reservoirs that are relatively shallow and do not cool to the temperature of maximum density.

(2-1.4) For estuary models, the model should include capability to treat lagoonal and channel estuaries.

Comments: Applicability of these criteria were to be judged by statements in the literature references to the model, especially review papers, and the extent of operation for specific catchments and/or watercourses.

(1-2) The model should be coded in an operating computer program for general applicability.

(1-2.1) The model should be capable of copying and distribution, and either be in the public domain or flexible in its licensing requirements.

(1-2.2) The model should be reasonably capable of transporting to a variety of PC platforms.

(2-2.3) The source code must be available to potential users.

Comments: Implementation of the model in some sort of computer-based computational framework was to be judged by statements in the literature references to the model. At this level of evaluation, Criterion (2-2.2) could be satisfied by statements about the source programs (and requisite compilers), the platform upon which the model operates, and/or reported experience in operating the model on a variety of machines. With respect to (2-2.3), any indication that *only* the executables are available was considered to be sufficient to exclude the model from further consideration.

(2-3) The model program should have a satisfactory lineage.

(2-3.1) The model must have a sufficient history of application, which we require to be at least five (5) years in more-or-less its current form of application to the watercourse system(s) of relevance to Texas.

(2-3.2) The model must be of sufficient currency, *viz*. the most recent application must have been made within the past ten (10) years.

Comments: The purpose of these criteria is to offer reasonable assurance that the computer implementation of a model has received adequate testing in *realistic* applications, and that the model code is at a reasonably modern standard. The above year requirements are somewhat arbitrary, and were not applied with great precision whenever they were the only criterion by which a candidate model was excluded.

(2-4) The model should be fundamentally mechanistic, i.e. deterministic, in concept.

Comments: Purely statistical models are limited in their range of application, and the conditions for which they may be employed, both of which can significantly hamper the utility of the model in management strategies. This criterion does not preclude the use of semi-empirical or statistical sub-models (which are unavoidable), but does require an overall deterministic formulation. Ward and Benaman (1999) discuss and contrast statistical and deterministic models.

The Level-1 screening criteria were formulated in a series of checklist questions, given in Table 2-1.

Table 2-1
Level-1 screening checklist

Watershed models, capabilities:		
low-relief terrain, semi-arid to subhumid basins	❑ yes	❑ no
basins dominated by fluvial drainageways	❑ yes	❑ no
substantially altered hydrology due to storage and conveyance systems	❑ yes	❑ no
substantially altered hydrology due to urbanization	❑ yes	❑ no
Stream and river models, capabilities:		
flashy and low-baseflow rivers and tributaries	❑ yes	❑ no
streams dominated by fluvial-type bathymetry	❑ yes	❑ no
Lake and reservoir models, capabilities:		
run-of-the-river reservoirs	❑ yes	❑ no
relatively shallow lakes	❑ yes	❑ no
seasonal temperatures fall below that of maximum density	❑ yes	❑ no
Estuary models, capabilities		
lagoonal estuaries	❑ yes	❑ no
channel estuaries	❑ yes	❑ no
(2) Existence of model as operating computer program for general applicability. Model code:		
capable of copying and distribution	❑ yes	❑ no
in public domain	❑ yes	❑ no
flexible in its licensing requirements	❑ yes	❑ no
capable of transporting to variety of PC platforms	❑ yes	❑ no
source code available to potential users	❑ yes	❑ no
(3) Model program lineage.		
Sufficient history of application (at least five years in more-or-less current form of application to watercourse of relevance to Texas)	❑ yes	❑ no
Sufficient currency (most recent application within the past ten years)	❑ yes	❑ no
(4) Model conceptual philosophy		
Deterministic	❑ yes	❑ no

2.2 Screening Level 2 Criteria

The Level-2 review criteria were more sharply focused than those of Level 1, addressing specific features of the model under review, but at the same time were less formal, to better accommodate the range of variation in model strategy, formulation and coding. These criteria enumerated aspects of the technical basis of the model to be sought in literature reviews and to form the information base for comparative evaluations.

The specific technical aspects of a model differ according to the watercourse addressed. Consequently, a distinction is made between the criteria appropriate for watershed models and those for receiving streams. (Lakes and estuaries are considered to represent special aquatic environments, with specialized modeling requirements. These are addressed separately and evaluated on an *ad hoc* basis.)

2.2.1 Watershed model criteria (Level-2)

(2-1) The model should be formulated to allow depiction of features characteristic of Texas catchments.

(2-1.1) Does the model differentiate soil types, vegetation cover, land-use categories, and topography? What is the basis for such differentiation (e.g., categories, parameters)?

(2-1.2) What is the basis for determination of runoff and the disposition of surface flow?

(2-1.3) What is the basis for modeling mobilization and transport of sediment and waterborne constituents? What parameters are presently included in the model formulation?

(2-1.4) What are the scales of temporal and spatial integration underlying the model formulation?

(2-1.5) What features of the model formulation are considered extraneous to Texas concerns, and to what extent do these extraneous concerns dominate model development and capabilities?

(2-2) The numerical solution embodied in the model should be at a level of generality adequate for adaptation to Texas basins.

(2-2.1) What is the method(s) for numerical specification of the terrain and drainage network?

(2-2.2) What is the level of automation by which the numerical schemata of (2.1) are delineated, and its physical basis? This criterion includes grid-definition and I/O data handling requirements.

(2-3) The computer coding should accommodate generality of application and be amenable to modification, especially for models whose formulation or application has not been germane to Texas basins.

(2-3.1) What are the properties of the source code(s), e.g. language, versions, portability, linkage?

(2-3.2) What are the hardware requirements for the model? What level of computer resources is required?

(2-3.3) To what extent has model operation been coupled with other related models, e.g., groundwater, receiving waters? In particular, how does the model couple with a stream/river model?

Comments: Unlike the exclusionary formulation of the Level-1 Criteria, these criteria require determination of specific aspects of the model formulation, by which models were evaluated on a comparative basis. The central rôle of the watershed model in determination of TMDL's dictates that these candidate models be evaluated on a priority basis. Of equal importance are the stream/river ("receiving water") models addressed separately in the next section. As noted above, watercourses such as lakes, reservoirs, bays and estuaries are considered to be special-purpose problems, and the review of candidate models was much more narrowly focused and performed in a later stage of the review process.

To facilitate application of these criteria, they were distilled to a checklist format, as shown in Table 2-2. Unlike those of Table 2-1, these are not exclusionary, but merely a compact means of displaying model properties for comparative purposes.

2.2.2 Stream and river model criteria (Level-2)

(2-1) The model should be formulated to allow depiction of features characteristic of Texas rivers and streams.

(2-1.1) Does the model differentiate channel geometries and bed characteristics?

(2-1.2) What are the scales of temporal and spatial integration underlying the model formulation?

(2-1.3) What is the basis for determination of advective and dispersive transports? How is longitudinal current computed from boundary controls? Does the model impose criticality constraints, or accommodate transitions in criticality of flow?

(2-1.4) What is the basis for modeling mobilization and transport of sediment and waterborne constituents? What parameters are presently included in the model formulation?

Table 2-2
Level-2 screening checklist for watershed models

---

(1) Model formulation

differentiation of soil types, vegetation, land-use? ❏ yes ❏ no

Review basis for such differentiation (e.g., categories, parameters)

satisfactory determination of runoff? ❏ yes ❏ no

satisfactory disposition of surface flow? ❏ yes ❏ no

Review basis for determination of runoff and the disposition of surface flow. How are channels depicted and input into the model?

sediment mobilization & transport included? ❏ yes ❏ no

Review basis for modeling mobilization and transport of sediment and waterborne constituents, especially with regard to parameters presently included in the model formulation. Survey input requirements.

temporal integration: ❏ event only ❏ continuous

Determine capability of model for interevent hydrological processes, e.g. evapotranspiration, desiccation of watershed, plant uptake.

receiving water: ❏ included in model ❏ external link ❏ none

inclusion of features extraneous to Texas? ❏ yes ❏ no

(2) Numerical solution

method for numerical specification of terrain and drainage network:

❏ manual input ❏ import of standard files ❏ GIS

Review method(s) for numerical specification of the terrain and drainage network, including the level of automation by which the numerical schemata are delineated, and its physical basis? This criterion includes grid-definition and I/O data handling requirements.

numerical solution method (spatial)

❏ finite-difference ❏ finite element ❏ boundary element ❏ other

(3) Implementation for computer operation

properties of source code:

❏ FORTRAN ❏ C ❏ Visual BASIC ❏ other

hardware requirements of model:

❏ PC compatible ❏ workstation or high-end PC ❏ Macintosh

❏ Supercomputer (e.g., Cray) ❏ other ❏ unknown

Review extent to which other models are coupled, either within model code or through export of output file.

(2-1.5) Can the model be generalized to include lakes and/or estuaries in its formulation? How is the depiction of these systems limited by criteria (1.1)-(1.4)?

(2-1.6) What features of the model formulation are considered extraneous to Texas concerns, and to what extent do these extraneous concerns dominate model development and capabilities?

(2-2) The numerical solution embodied in the model should be at a level of generality adequate for adaptation to Texas streams and rivers.

(2-2.1) What is the method(s) for numerical specification of the riverine system?

(2-2.2) What is the level of automation by which the numerical schemata of (2.1) are delineated, and its physical basis? This criterion includes grid-definition and I/O data handling requirements.

(2-3) The computer coding should accommodate generality of application and be amenable to modification, especially for models whose formulation or application has not been germane to Texas rivers.

(2-3.1) What are the properties of the source code(s), e.g. language, versions, portability, linkage?

(2-3.2) What are the hardware requirements for the model? What level of computer resources is required?

(2-3.3) To what extent has model operation been coupled with other related models, e.g., groundwater, lakes or estuaries? In particular, how does the model flange with a watershed model?

Comments: The modeling of streams and rivers has the longest history in water-quality management, and a rich selection of models has been accumulated over the years of development. There are also numerous reviews of stream and river models in the scientific literature. The above criteria therefore focus on specific aspects of stream and river modeling essential to TMDL development in Texas. These include the generality of the model, whether it is capable of depicting "flashy" or "storm" hydrographs, which will be important in many TMDL's in Texas, whether it includes parameters, such as suspended sediment, that are carriers of watershed-derived contaminants, or includes parameters considered to be involved in nonpoint pollution in Texas watercourses. Another aspect of model review is the ease with which the stream/river model can accommodate loads generated from a watershed model.

As with the watershed models, application of these criteria was facilitated by succinctly presenting these in checklist format, as shown in Table 2-3. Again, in contradistinction to the criteria of Table 2-1, these are not exclusionary, but merely a compact means of displaying model properties for comparative purposes.

2.3 Screening Level 3 Criteria

Level-3 criteria were applicable to stream/river and watershed models only. The Level-3 criteria were formulated to have considerable overlap with those of Level-2, addressing many of the same features of a candidate model, but in more detail and with more emphasis on the operational capabilities of the model. As is the case for the Level-2 criteria, these criteria serve as a review "check-list" for model characteristics, and in this report are presented in a narrative text (unlike the itemized Level-1 and Level-2 criteria). Some of the more important Level-2 and Level-3 attributes are reviewed comparatively in the tabulations of Ward and Benaman (1999).

Table 2-3
Level-2 screening checklist for stream and river models

---

(1) Model formulation

variable channel geometry? ❏ yes ❏ no
variable bed characteristics? ❏ yes ❏ no
Describe how channel geometry and bed characteristics are handled.
time integration: ❏ steady-state only ❏ time varying
accommodates flood-type hydrograph? ❏ yes ❏ no
Summarize scales of temporal and spatial integration underlying the model formulation. (E.g., steady state, slowly varying dynamic, fully dynamic event)
basis for current computation: ❏ direct input ❏ continuity only
❏ kinematic wave ❏ complete hydraulic model ❏ other
Describe basis for determination of advective and dispersive transports
water quality (mass transport) capability included? ❏ yes ❏ no
Summarize parameters and kinetics included.
sediment dynamics in stream included? ❏ yes ❏ no
peripheral sediment loads included? ❏ yes ❏ no
Summarize basis for modeling mobilization and transport of sediment and waterborne constituents. What parameters are presently included in the model formulation?
capability to include channel estuaries or run-of-river reservoirs? ❏ yes ❏ no
Summarize features of the model formulation considered extraneous to Texas concerns, and to what extent these extraneous concerns dominate model development and capabilities?

(2) Numerical solution

method for numerical specification of stream channel and network:
❏ manual input ❏ import of standard files ❏ GIS
Review method(s) for numerical specification of the stream/river geometry, including the level of automation by which the numerical schemata are delineated, and its physical basis? This criterion includes segment-definition and I/O data handling requirements.
numerical solution method (spatial)
❏ finite-difference ❏ finite element ❏ boundary element ❏ other

(3) Implementation for computer operation

properties of source code:
❏ FORTRAN ❏ C ❏ Visual BASIC ❏ other
hardware requirements of model:
❏ PC compatible ❏ workstation or high-end PC ❏ Macintosh
❏ Supercomputer (e.g., Cray) ❏ other ❏ unknown
Review extent to which other models are coupled, either within model code or through input/export of file.
has the model been routinely flanged with a watershed model? ❏ yes ❏ no

---

2.3.1 Watershed model criteria (Level-3)

(3-1) The model should be adequately demonstrated to successfully simulate catchments typical of Texas and have a satisfactory level of technical acceptance by scientists and engineers.

(3-1.1) Does the history of application indicate suitability for Texas watersheds? To what extent and for what range of parameters has model validation been achieved? Summarize the technical regard for the model in the technical community.

(3-1.2) Determine the level of accuracy achievable with the model, based upon systematic comparison with appropriate field data. (Differentiate direct comparison to runoff quality in contrast to validation against receiving watercourse measurements.) To what extent is the accuracy impaired by numerical constraints (spatio-temporal discretization, numerical integration methods, spurious dispersion or mass-conservation failure) in comparison to errors in input or parameter specification?

(3-2) The model should be capable of adaptation to specific water-quality management problems encountered in Texas basins.

(3-2.1) Is the coding and/or input of the model such that parameters, constants, and other inputs can easily be modified for model calibration? How accessible is the model to modifications or customization? Does the model lend itself to be modified for other constituents?

(3-2.2) How does the model operation handle time varying inputs and outputs for events with substantial temporal variation? Has the model been successfully applied to storm runoff events? How would model I/O be managed to reflect statistics of seasonality or climate variation?

(3-2.3) Have there been applications of the candidate model to the specific problem of nonpoint-source load determination? Assess the reported effectiveness of the model.

(3-3) The model should be capable of implementation in a GIS environment with features to facilitate user operation (at a level of simplicity appropriate to the nature of the technical problem).

(3-3.1) To what extent has the model been operated with a GIS front-end? How has it been, or could it be, coupled with GIS, specifically ArcView?

(3-3.2) Determine types and resolution of critical data sets (initial/ boundary conditions, rate constants, terrain/soil parameters, etc.) vital to the accuracy of the model? To what extent do this limit or facilitate model operation in conjunction with GIS?

(3-3.3) Assess the computational resources required for model operation, and the extent to which these are determined by numerical features of the model programming and operation, in contrast to the actual integration of the governing equations and resolution of the solution.

(3-3.4) Are there aspects of model set-up, operation or output management that could be significantly improved by GUI in a GIS environment? Cogent display of results and coupling to analytical routines are particularly important (cf., Clean Rivers Program).

2.3.2 Stream and river model criteria (Level-3)

(3-1) The model should be adequately demonstrated to successfully simulate streams or rivers typical of Texas and have a satisfactory level of technical acceptance by scientists and engineers.

(3-1.1) Does the history of application indicate suitability for Texas rivers? To what extent has model validation been achieved and for what range of parameters? Summarize the technical regard for the model in the technical community.

(3-1.2) Determine the level of accuracy achievable with the model, based upon systematic comparison with appropriate field data. To what extent is the accuracy impaired by numerical constraints (spatio-temporal discretization, numerical integration methods, spurious dispersion or mass-conservation failure) in comparison to errors in input or parameter specification?

(3-2) The model should be capable of adaptation to specific water-quality management problems encountered in Texas rivers and streams.

(3-2.1) Is the coding and/or input of the model such that parameters, constants, and other inputs can easily be modified for model calibration? How accessible is the model to modifications or customization? Does the model lend itself to be modified for other constituents or for coupled reactions?

(3-2.2) How does the model operation handle time varying inputs and outputs for events with substantial temporal variation? Has the model been successfully applied to storm hydrograph events? How would model I/O be managed to reflect statistics of seasonality or climate variation?

(3-2.3) Have there been applications of the candidate model to the specific problem of water-quality response to nonpoint-source loads, notably storm runoff events? Assess the reported effectiveness of the model.

(3-3) The model should be capable of implementation in a GIS environment with features to facilitate user operation (at a level of simplicity appropriate to the nature of the technical problem).

(3-3.1) To what extent has the model been operated with GIS determined inputs, either with or without an associated watershed model?

(3-3.2) Determine types and resolution of critical data sets (initial/ boundary conditions, rate constants, transport parameters, etc.) vital to the accuracy of the model? To what extent do this limit or facilitate model operation in conjunction with watershed models and/or a GIS front-end?

(3-3.3) Assess the computational resources required for model operation, and the extent to which these are determined by numerical features of the model programming and operation, in contrast to the actual integration of the governing equations and resolution of the solution.

(3-3.4) Are there aspects of model set-up, operation or output management that could be significantly improved by GUI in a GIS environment with or without a coupled watershed model? Cogent display of results and coupling to analytical routines are particularly important (cf., Clean Rivers Program).

(3-4) Assess the extent to which the model may be extended, with minimal re-programming, to depiction of special watercourses in Texas, *viz*. lakes, reservoirs, estuaries and bays.

2.3 Screening Level 4 Criteria

Models designed for application to lakes and reservoirs are regarded as special-purpose models for this review. These apply to large, spatially complex watercourses with long detention times, and have the possibility of developing seasonal stratification. Moreover, when the waterbody is created by a dam (the only case of any significance in Texas), operation of the dam becomes an important control on the transport and water quality of the reservoir, which must be accommodated in the model.

Similarly, the estuary and/or coastal embayment is a complex watercourse that requires a special-purpose model. The Texas embayments are broad systems with variable geometry that connect with the sea through relatively narrow inlets. The watercourses can be affected by hydrological forcing from their watersheds, but also by the marine factors of tides, meteorological forcing of the coastal ocean, and variable density due to intermixing of fresh and salt water. A model must be capable of depicting all of these combinations of external factors.

We note that many stream/river models can be adapted to modeling both a run-of-the-river reservoir and a longitudinal estuary. In the case of the former, the physical characteristics of reservoirs amenable to this sort of modeling are much more limited, e.g. relatively shallow systems with frequent hydrological replacement. Many reservoir environments in Texas cannot be adequately addressed with such a spartan modeling formulation, so the need for more general, special-purpose reservoir models is apparent. In the case of the latter, the estuary must be dominated by its longitudinal dimension, so that variation of water quality with position in the system can be adequately addressed as section-mean values. Moreover, the processes of tidal oscillation and salinity intrusion must be amenable to parameterization by an effective dispersion coefficient. These conditions may apply to the tidal or saline reach of Texas rivers, but clearly are not satisfied by the Texas embayments. While it is not yet clear to what extent reservoirs or embayments will require TMDL determinations, there is certainly a potential for requiring a suitable special-purpose model, so these were included in the Level-4 screening category.

Because these are special-purpose models, they were reviewed with a set of criteria that better targeted specific aspects of these types of models. The criteria for lake and reservoir models are summarized in Table 2-4, and those for estuary and bay models are given in Table 2-5. These criteria take the place of the Level-2 and Level-3 screening for the other types of watercourses, and therefore overlap to a certain extent with those criteria, though with the special twists entailed by these complex watercourses. In the reviews, the results of these screenings are presented both in the checklist format of Tables 2-4 and 2-5, and in narrative reviews of the models.

Table 2-4
Level-4 screening checklist for special-purpose lake and reservoir models

---

(1) Model formulation

spatial depiction: ❑ one-dimensional longitudinal ❑ two-dimensional horizontal ❑ two-dimensional longitudinal-vertical ❑ three-dimensional

variable geometry? ❑ yes ❑ no

variable bed characteristics? ❑ yes ❑ no

Describe how channel geometry and bed characteristics are handled.

time integration: ❑ steady-state only ❑ fully time varying ❑ slowly varying (long term averaging, e.g. monthly)

accommodates riverine hydrographs? ❑ yes ❑ no

includes stratification (density variation)? ❑ yes ❑ no

basis for current distribution: ❑ direct input ❑ continuity only ❑ separate hydrodynamic model ❑ integral hydrodynamic model ❑ other

basis for vertical diffusivity: ❑ direct input ❑ constant ❑ turbulence sub-model in hydrodynamics ❑ other

heat budget and temperature capability included? ❑ yes ❑ no

ice formation included? ❑ yes ❑ no

water quality (mass transport) capability included? ❑ yes ❑ no

Summarize parameters and kinetics included.

sediment dynamics in reservoir included? ❑ yes ❑ no

peripheral sediment loads included? ❑ yes ❑ no

Summarize basis for modeling mobilization and transport of sediment and waterborne constituents. What parameters are presently included in the model formulation?

Summarize features of the model formulation considered extraneous to Texas concerns, and to what extent these extraneous concerns dominate model development and capabilities?

(2) Numerical solution

method for numerical specification of reservoir geometry:

❑ manual input ❑ import of standard files ❑ grid generator ❑ GIS

Review method(s) for numerical specification of lake/reservoir geometry, any mathematical transforms employed, and the level of automation by which the computational grid is delineated, and its physical basis? This criterion includes element-definition and I/O data handling requirements.

numerical solution method (spatial)

❑ finite-difference ❑ finite element ❑ boundary element ❑ other

for hydrodynamic models with coupled density, any special treatment of vertical diffusivity terms? ❑ yes ❑ no

(3) Implementation for computer operation

properties of source code:

❑ FORTRAN ❑ C ❑ Visual BASIC ❑ other

(continued)

Table 2-4
(continued)

---

minimum hardware requirements of model:

❏ PC compatible ❏ workstation or high-end PC ❏ Macintosh

❏ Supercomputer (e.g., Cray) ❏ other ❏ unknown

has the model been routinely flanged with a watershed model? ❏ yes ❏ no

(4) Suitability for Texas lake/reservoir systems.

Demonstrated application to lakes/reservoirs typical of Texas? ❏ yes ❏ no

Acceptable performance in model validation studies? ❏ yes ❏ no

Acceptable level of technical acceptance? ❏ yes ❏ no

Summarize history of application supporting suitability for Texas reservoirs, and the range of parameters.

Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ❏ yes ❏ no

Does model coding/input accommodate alternative reservoir operation rules? ❏ yes ❏ no

power-plant heat loads? ❏ yes ❏ no

Summarize how model operation handles time varying inputs and outputs for events with substantial temporal variation. Has the model been successfully applied to systems with dynamic riverine inputs?

Assess the computational resources required for model operation.

(5) Capability for implementation in a GIS environment.

Has model been operated with GIS derived inputs, either with or without an associated watershed model? ❏ yes ❏ no

Has model output been displayed using modern visualization capabilities? ❏ yes ❏ no

Summarize types and resolution of critical data sets (initial/ boundary conditions, rate constants, transport parameters, etc.) vital to the accuracy of the model. To what extent do this limit or facilitate model operation in conjunction with watershed models and/or a GIS front-end?

Are there aspects of model set-up, operation or output management that could be significantly improved by GUI in a GIS environment with or without a coupled watershed model?

Table 2-5
Level-4 screening checklist for estuary and coastal embayment models

---

(1) Model formulation

spatial depiction: ❑ one-dimensional longitudinal ❑ two-dimensional horizontal
❑ two-dimensional longitudinal-vertical ❑ three-dimensional

variable geometry? ❑ yes ❑ no

variable bed characteristics? ❑ yes ❑ no

Describe how channel geometry and bed characteristics are handled.

time integration: ❑ steady-state only ❑ time varying tidal-mean
❑ fully time varying

accommodates riverine hydrographs? ❑ yes ❑ no

includes gravitational circulation (density variation)? ❑ yes ❑ no

basis for current distribution: ❑ direct input ❑ continuity only
❑ separate hydrodynamic model ❑ integral hydrodynamic model ❑ other

water quality (mass transport) capability included? ❑ yes ❑ no

Summarize parameters and kinetics included.

sediment dynamics in estuary included? ❑ yes ❑ no

peripheral sediment loads included? ❑ yes ❑ no

Summarize basis for modeling mobilization and transport of sediment and waterborne constituents. What parameters are presently included in the model formulation?

Summarize features of the model formulation considered extraneous to Texas concerns, and to what extent these extraneous concerns dominate model development and capabilities?

(2) Numerical solution

method for numerical specification of estuary geometry:
❑ manual input ❑ import of standard files ❑ grid generator ❑ GIS

numerical solution method (spatial)
❑ finite-difference ❑ finite element ❑ boundary element ❑ other

Review method(s) for numerical specification of estuary geometry, any mathematical transforms employed, and the level of automation by which the computational grid is delineated, and its physical basis? This criterion includes element-definition and I/O data handling requirements.

for hydrodynamic models with coupled density, scale separation or mode-splitting?
❑ yes ❑ no

(3) Implementation for computer operation

Source code:

❑ FORTRAN ❑ C ❑ Visual BASIC ❑ other

(continued)

Table 2-5
(continued)

Minimum hardware requirements of model:
❏ PC compatible ❏ workstation or high-end PC ❏ Macintosh
❏ Supercomputer (e.g., Cray) ❏ other ❏ unknown
Has the model been routinely flanged with a watershed model? ❏ yes ❏ no
Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ❏ yes ❏ no

(4) Suitability for Texas estuarine systems.
Demonstrated application to bays or estuaries typical of Texas? ❏ yes ❏ no
Acceptable performance in model validation studies? ❏ yes ❏ no
Acceptable level of technical acceptance? ❏ yes ❏ no
Summarize history of application supporting suitability for Texas bays & estuaries, and the range of parameters

(5) Capability for implementation in a GIS environment.
Has model been operated with GIS derived inputs, either with or without an associated watershed model? ❏ yes ❏ no
Has model output been displayed using modern visualization capabilities?
❏ yes ❏ no
Summarize types and resolution of critical data sets (initial/ boundary conditions, rate constants, transport parameters, etc.) vital to the accuracy of the model. To what extent do this limit or facilitate model operation in conjunction with watershed models and/or a GIS front-end?
Are there aspects of model set-up, operation or output management that could be significantly improved by GUI in a GIS environment with or without a coupled watershed model?

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3. MODEL REVIEWS

In this chapter —which comprises the bulk of this report— are presented summary reviews of each of the individual models considered in this project. The reviews are organized alphabetically by model name. Each review is intended to be an autonomous report, including a narrative discussion of the model, bibliographic citations, and information on availability of the model code, although occasionally the reviews of several closely related models are coordinated and cross-referenced, such as the USDA models SWRRB and SWAT, or the one-dimensional river models QUAL2E and QUALTX. These reviews formed the basis for the companion report in this project (Ward and Benaman, 1999), which presents a more general discussion of the modeling process within TMDL development, including treatment of generic aspects of watercourse modeling.

Each review includes a summary checklist of that model's evaluation utilizing the Level-1 screening criteria, see Table 2-1 above, following by a decision:

Level-1 Screening: ☐ eliminate ☐ consider

of whether that model would receive further consideration in the review process or be eliminated at the Level-1 stage. For those that pass this screen, the results of the Level-2 review are presented in both checklist form (see Tables 2-2 and 2-3) and as a narrative discussion. Again, a decision is documented:

Level-2 Screening: ☐ eliminate ☐ consider

Because the Level-3 criteria function more as a guide for the review than a pass/fail criterion for elimination, their results are presented in the narrative discussion, which summarizes the adherence of the model to the Level-3 criteria, as well as any other attributes of a particular model that may be relevant to its utility in a TMDL process.

Model: **ADAPT (Agricultural Drainage And Pesticide Transport)**

Source:
Dr. Andy Ward
Food, Agriculture & Biological Engineering
230B Agricultural Engineering
Ohio State University
590 Woody Hayes Dr
Columbus, Oh 43210

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds (field-scale)

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☐ yes	☐ no
in public domain	☐ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

[no information available, see discussion below.]

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☐ yes ☐ no
(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

ADAPT is a recent "research" model, an extension of GLEAMS to include chemical transport to the water table. Developed by Dr. Andy Ward at Ohio State, ADAPT uses transport and chemical reaction subroutines from the NCSU vadose-zone model DRAINMOD. A second model BESTAQUA is under development, which will employ built-in values of soil and drainage parameters appropriate to Midwest regions in a Windows interactive front-end to ADAPT, and thereby simplify the input requirements of the user.

The only literature references found in this review are publications of the model developer and his colleagues and students, e.g. Desmond et al. (1995, 1996) and Chung et al., (1992). Desmond et al. (1996) report application of the model to a subsurface-drain equipped field near Aurora, North Carolina. They compared predicted water table depths for ADAPT, DRAINMOD, SWATREN and PREFLO, finding essentially equivalent results.

No information is available on the coding, source language, and distribution of ADAPT.

Model:	**AGNPS (Agricultural Nonpoint Source Pollution Model)**
Source:	Agricultural Research Service U.S. Dept. of Agriculture Grassland, Soil & Water Research Laboratory 808 East Blackland Road Temple, TX 76502

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☐ yes	☑ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic	☐ yes	☑ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

Developed by the Soil Conservation Service (now Natural Resource Conservation Service) and Agricultural Research Service, AGNPS, as the name implies, is a watershed model intended for application to agricultural catchments, with its initial application to the northern Plains states (Young et al., 1995). It is a distributed model in the sense that watershed geometry is represented by discrete elements (uniformly distributed squares). The major components are runoff (driven by precipitation), infiltration, fertilizer application, and surface loading. Although the basic structure of the model is process-based, the key components are empirical, hence it is classified as a "statistical" model. Volume of runoff from a watershed element is determined by the SCS curve number method and erosion by the USLE. Distributary channels are considered to be embedded in the watershed elements, in which triangular hydrographs with peak flow given by an empirical equation dependent upon drainage area, channel slope and shape parameters of the watershed. Surface sediment mobilization is computed from the USLE and transport capacity is based upon Bagnold stream power equation. Chemical transport of N, P, and COD in both dissolved and suspended (adsorbed) forms from the watershed by runoff is computed as loads.

AGNPS is an "event" model. It is initialized with soil and landscape conditions prior to occurrence of a storm and computes the response of the catchment to the storm event, including loadings in the runoff. It does not track changes in the watershed between storm events.

AGNPS has been widely used in recent years, especially in the Midwest. A disappointingly large proportion of the applications are simulation exercises to evaluate model-predicted responses to land-use changes, especially agricultural practices, with a smaller proportion using field data for "calibration" purposes, and a very small proportion actually addressing the accuracy of the model by comparison to observations. For example, McIntosh et al. (1993) applied three models (EPIC, AGNPS and SWRRB) to evaluating sediment-loading reductions in dairy farm watersheds in Wisconsin. Holmberg et al. (1998) made comparative runs of AGNPS and EPIC to evaluate fertilizer application strategies. Sugiharto et al. (1994) describe a similar exercise in applying AGNPS and EPIC to sediment and phosphorus loadings under twenty (count them, 20) different management strategies for dairy-farm dominated watershed. Foerster and Milne-Home (1995) report an application in Wales to a "conservation tillage trial site". The hydrology submodel was calibrated with five storm events, and various management practices were comparatively evaluated. . Corbett et al., (1997) evaluated AGNPS for two watersheds beyond the types for which the model was initially developed, viz. a forested watershed in coastal South Carolina and an urbanized watershed, examining storm water runoff volumes, flow rates and sediment loads. The hydrologic submodel was calibrated with 10 rain events and model simulations of the two watersheds were compared. While the model was stated to perform for these types of watershed, it appears no model validation was actually carried out. Other literature publications are even more limited to simple sensitivity analyses.

In its original form, much labor was necessary to develop the input file(s) for AGNPS, but in recent years some work has been carried out coupling AGNPS to a GIS framework. Mitchell et al, (1989) report integration of AGNPS with the Geographic Resource Analysis Support System (GRASS). They applied AGNPS to predicting runoff and sediment load from small watersheds of mild topography, based on fifty sediment yield events from two watersheds and five nested subwatersheds in East Central Illinois. (Half of these events were used to calibrate parameters in AGNPS.) Panuska et al. (1991) is an "early" example of integrating Terrain analysis methods into the pre-processing of AGNPS applications. They produced both a contour-based version and a grid-based version. He et al. (1993) combined AGNPS with GRASS, and GRASSWATERWORKS (a hydrologic modeling "tool box" under development at Michigan State University) to evaluate the impact of agricultural nonpoint source runoff on a subwatershed of Saginaw Bay. Liao and Tim (1997) criticize existing interfaces linking GIS to distributed watershed models as ad-hoc and limited to organization of input data and display of output data. They report development of "a highly interactive water quality modeling interface", viz. ARC-INFO.

Some of these GIS-AGNPS combinations have evaluated model response to processing of the distributed terrain input. Kao and Hong (1995) describe an application in which drainage patterns generated from DEM data was used to generate input for AGNPS. Again, GRASS was the GIS employed. They implemented a case study for the watershed of the Po-San off-stream reservoir, and found significant spatial variation of pollution distribution resulting from different drainage pattern generating methods. A related computational experiment is reported by Srinivasan et al., (1994), who tested four different techniques for estimation of slope from digital elevation data sets, viz. neighborhood, quadratic, best fit plane, and maximum slope method, with respect to computed slope percentages, slope lengths, and erosion estimates. They used the GRASS GIS combined with AGNPS in a test application to a 124-ha watershed located in Waco County, Texas, finding "notable differences" among the predicted erosion. Fisher et al. (1997) compared the sensitivity of AGNPS and ANSWERS to random re-arrangement of soil and terrain data, finding that both models were insensitive to this information, which raises serious question about "whether they repay their computational complexity." The unstated question, of course, is whether runoff and loadings from real watersheds are similarly insensitive to the actual spatial distribution of soil and terrain features.

Line et al. (1997) also developed an interface with GRASS (referred to as WATERSHEDSS), which automatically computes input data from basic soils, topography and land use maps, and was applied to simulate runoff and sediment, nitrogen, and phosphorus loads for a watershed in North Carolina. Model predictions were compared to observed runoff and pollutant load at two monitoring stations for 11 storms, for which the model performance was "satisfactory." Kao et al. (1998) report a follow-up study, in which loads produced by AGNPS were input to WASP applied to the downstream reservoir, in which data were to be collected for validation of phosphorus loads and in-lake phosphorus concentrations.

A frequent target when field data are available for model evaluation is the runoff-curve method, which underlies so much of the hydrology. McCool et al. (1995) evaluated several such models including AGNPS (as well as EPIC and CREAMS) using runoff plot data from the Palouse Conservation Field Station near Pullman, Washington. They calculated runoff index values from this data, and found them to be considerably higher than the usual curve numbers. It is noted that the frozen soil areas of the Pacific Northwest depart considerably from the data from which the original curve numbers were derived, so this may not be a weakness so much as an extension of the basic method. Needham and Young (1993) modified AGNPS for an annualized output, rather than an event output, employing "enhanced" revised Universal Soil Loss Equation (RUSLE) routines. The resulting model ANN-AGNPS was compared to observations of a single storm and found to perform "reasonably well." Renard and Ferreira (1993) describe RUSLE as a computer-based model, which employs new relationships to estimate values of the six factors in the USLE equation.

Perrone and Madramootoo (1997) evaluated the predictive capability of AGNPS with respect to surface runoff, peak flow, and sediment yield produced by rainfall-runoff events on a 26 sq-km watershed in Quebec. Seven rainfall-runoff events were used for model calibration. Five storms were used to validate the model. "Calibration curves" were developed to correlate the antecedent precipitation index (API) to the SCS curve number. For model calibration, coefficients of performance of 0.12, 0.05, and 0.43 were obtained for peak flow, surface runoff, and sediment yield, respectively. For model validation, coefficients of performance of 0.02, and 0.01 were obtained for surface runoff, and sediment yield, respectively. Peak flow was generally overpredicted and yielded a coefficient of performance of 2.07. One of the more comprehensive evaluations was performed by Wu et al. (1993), who compared data on runoff and sediment yield for 30 runoff events from three experimental watersheds to the model predictions of AGNPS, CREAMS and ANSWERS. They found the computed and measured runoffs to show "reasonable to poor agreement," and all three models to underestimate sediment yield for large storms. Bingner et al. (1989) carried out a similar comparison of ANSWERS, CREAMS, SWRRB, EPIC and AGNPS using data from Mississippi research watersheds, and found AGNPS to perform satisfactorily compared to measurements but were critical of its inability to update parameters in extended simulations.

Reference is made to the following web site for additional information on AGNPS and copies of the model:

ftp://ftp.nrcs.usda.gov/centers/itc/applications/wqmodels/agnps/

A recent modification of AGNPS, designated AGNPS 98, is available from:

http://www.sedlab.olemiss.edu/AGNPS98.html

This model appears to still be under development. No citations documenting its use were found.

Model: **ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation)**

Source: Dr. David Beasley
Biological and Agricultural Engineering Department
Campus Box 7625
North Carolina State University
Raleigh, NC 27695-7625

Also:
Agricultural Engineering Department
University of Georgia
Coastal Plain Experiment Station
Tifton, GA 31973-0748

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria (watershed models)

(1) Model formulation

differentiation of soil types, vegetation, land-use? ☑ yes ☐ no

satisfactory determination of runoff? ☑ yes ☐ no

satisfactory disposition of surface flow? ☑ yes ☐ no

sediment mobilization & transport included? ☑ yes ☐ no

temporal integration: ☑ event only ☐ continuous

receiving water: ☐ included in model ☐ external link ☑ none

inclusion of features extraneous to Texas? ☑ yes ☐ no

(2) Numerical solution

method for numerical specification of terrain and drainage network:
☑ manual input ☐ import of standard files ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Level-2 Screening: ☐ **eliminate** ☑ **consider**

Discussion

ANSWERS is one of the first general-purpose distributed process models designed for application to agriculture-dominated watersheds (Beasley et al., 1980, Beasley and Huggins, 1991). For this reason, it was also one of the earliest models to be adapted for GIS-processed input, and has been used in several studies of data input sensitivity and scale resolution.

ANSWERS is an "event" model, intended to apply to runoff processes during and immediately after a rainfall event. Model set-up begins with schematizing the watershed into a network of square grid elements, each of which is assumed to be homogeneous in physical properties. The user specifies the magnitude and direction of slope for each element. This is used by the model to compute the rate of flow from the model element, using Manning's equation. Provision is included for subsurface tile drainage, again user-specified. There is a superposed independent depiction of the stream/tributary network as channel elements, each node of which is embedded in a watershed element. Since a watershed element can contain only one channel element, to depict complex or detailed channel networks requires additional refinement in the watershed elements. The user must specify the hydraulic properties of the channel elements.

The model is, of course, driven by rainfall, and is presently configured to accept no more than four rain gauges in the watershed. Parameters are included to represent vegetation interception, infiltration capacity and surface depression. As the potential for each of these is saturated, the surplus rainfall is assumed to move as runoff, the overland flow being computed by the above hydraulic relations. The infiltration model assumes a threshold value of surface detention that must be filled before runoff begins. This is, in turn, computed from a user-specified parameter of roughness, according the relations worked out by Huggins and Monke (1966). Infiltration is accumulated and used to drive a baseflow contribution to the channels, but Beasley and Huggins (1991) describe this part of the model as "crude." The model includes particle detachment and transport relations.

Solution of the Mannings Equation for hydraulic routing in the channel network is rather complicated, relying upon piecewise approximation to avoid the necessity of iterative solutions. Because of the complexity of the code, its authors recommend against someone attempting to modify the code unless intimately familiar with its structure.

The key hydrological process in ANSWERS is infiltration, as this rate controls accumulation of surface water and its conversion into runoff. Infiltration is based upon the theoretical model of Holtan (1961), which is based upon the concept of a "control zone" depth of soil that modulates downward flux of water, and requires six infiltration parameters (governed by soil type): total porosity, field capacity, depth of control zone, steady-state infiltration rate and two terms in the quasi-empirical time-varying equation, which have been quantified by controlled "rainulator" tests at USDA-ARS. The soil-loss component of ANSWERS is very close to being a purely statistical model, but it is properly regarded as a rational model with empirical coefficients. Interrill detachment is computed as proportional to the square of rainfall intensity (the coefficients including the USLE erodibility parameter) and overland detachment by a product formula very close to USLE. Rill and channel sediment transport is also a purely empirical formula, a power-law function of depth-mean velocity.

Clearly, ANSWERS in its present form places a great burden on the data input preparation task. Implementation of BMP's is accomplished by subroutines that overwrite the appropriate records in the input file to depict ponding, grass strips and similar strategies. The closest analog to ANSWERS appears to be AGNPS, which differs mainly in some of the hydrological terms, notably infiltration and runoff.

Wu et al. (1993) used data from 30 runoff events on three experimental watersheds in the North Appalachian experimental watershed in Ohio to carry out a comparative evaluation of

ANSWERS, CREAMS and AGNPS. They found that the models showed "reasonable to poor agreement" with measured runoff and sediment yield. The ANSWERS model provided the "most consistent estimates" of runoff and sediment yield, though, like the other two models, underestimating sediment yield for large storms. They found that the detachment models in ANSWERS and CREAMS range 0.9-1.0 and 0.4-1.6, respectively, for ratios of calculations to measurements. On the other hand, Bingner et al. (1989) carried out a similar comparison of ANSWERS, CREAMS, SWRRB, EPIC and AGNPS using data from Mississippi research watersheds, and found ANSWERS to have the poorest comparison to measurements.

De Roo (1993) coupled ANSWERS with a GIS front-end, and tested model predictions versus observations for two watersheds in the loess area of South Limburg (The Netherlands) and for a small watershed in Devon (UK). Some minor modifications were made to the saturated runoff (overland flow) computation. Despite this, the accuracy of the model for hydrograph prediction was variable, and for soil loss prediction rather poor, which de Roo attributes to the crusting formulation in the infiltration term. While conceding the utility of GIS-coupled distributed watershed modeling, he notes, "there is a substantial risk of gratuitous application." ANSWERS (as well as AGNPS and SWAT) was used by Engel et al. (1993) and Srinivasa and Arnold (1994) to evaluate efficiency of GIS integration with the distributed watershed model. They noted that for continuous-time, basin large-scale water quality models, collecting and manipulating the input data are more time-consuming and cumbersome due to the "method of disaggregation of the model", whose subdivisions are based on topographic boundaries. (It is not clear to these reviewers what was meant by this comment.) An example comparative application was made to an instrumented watershed in the Indian Pine Natural Resources Field Station near Purdue. No attempt was made to calibrate the models, but rather "roughly estimated" (as might be carried by a worker with little field data for guidance). Comparison with field data was poor (the error for runoff varying a factor of five about the actual value, and for sediment transport even larger, with no consistency among the models), perhaps a measure of the "risk of gratuitous application" noted by de Roo.

As noted in the discussion of AGNPS above, Fisher et al. (1997) compared the sensitivity of AGNPS and ANSWERS to random re-arrangement of soil and terrain data, finding that both models were insensitive to this information, which raises serious question about "whether they repay their computational complexity." On the other hand, Brown et al. (1993) used a front-end GIS to resample, format, and re-organize the model input data for iterative calculations of erosion and deposition for selected data aggregation levels, including 30, 60, 120, 180, 240, 300, 420, and 600 m square cells. They found that the changes in the model outputs at the selected levels of aggregation followed closely the changes in the spatial dependence of the input variables (as estimated through semivariograms). None of these studies bear on the viability of ANSWERS as a model, other than to demonstrate its relative ease of integration into a GIS shell.

The source code for ANSWERS is FORTRAN 77, and it has been adapted, and operates well, in a PC environment. The latest revisions of ANSWERS are dated 1988 (including some code to speed up the 80286 processor); see Beasley and Huggins (1991). Additional information is available from Dr David Beasley, the model developer, at:

beasley@eos.ncsu.edu

Model: **ANSWERS-2000 (Areal Nonpoint Source Watershed Environment Response Simulation - new version)**

Source: Dr. Theo A. Dillaha
Biological Systems Engineering Department
Virginia Tech
Blacksburg, VA 24061

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☑ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☑ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

ANSWERS-2000 is a new version of ANSWERS, under development at Virginia Polytechnic Institute by Dr. Theo Dillaha, one of Beasley's former students. ANSWERS-2000 differs from ANSWERS in two substantive ways (Bouraoui and Dillaha, 1996):

(1) better formulation of infiltration will be used, based upon the Green-Ampt equation;
(2) processes will be included to compute evapotranspiration and percolation, thus allowing the model to simulate conditions between rainfall events.

Because of (2), ANSWERS-2000 is a continuous-simulation model, in contrast to the "event" nature of ANSWERS.

The source code for ANSWERS-2000 is FORTRAN. According to Dillaha et al. (ca. 1998), a GIS-based frontend is also in development. No further information is available. The website cited in Dillaha et al. (1998a) is apparently disabled, no relevant links could be secured through Virginia Tech, and Dr Dillaha did not respond to our inquiries.

Model: **BATHTUB**

Source: Environmental Laboratory
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

lakes and reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	❑ yes	➢ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic	❑ yes	⋗ no

Level-1 Screening:	☑ **eliminate**	☐ **consider**

Discussion

BATHTUB is one of the array of watercourse programs developed by the Waterways Experiment Station to address various management and engineering aspects of watercourses affected by Corps projects. BATHTUB is part of a user-oriented PC-based eutrophication analysis program developed by WES for application to Corps of Engineers reservoirs, and is primarily the work of Walker (1981, 1987, 1996). The overall program package consists of three autonomous programs with the following functions:

FLUX	-	analysis of tributary loads into a reservoir
PROFILE	-	analysis of reservoir stratification and water-quality structure
BATHTUB	-	empirical determination of eutrophication "response" to pool nutrients

BATHTUB treats a reservoir component as a spatially-averaged control-volume segment with influxes and effluxes of volume and mass. The control volume is delineated by its morphological variables:

area
average depth
length
mixed-layer (epilimnion) depth
hypolimnetic depth

Up to 40 such segments can be defined and linked in a network. This means that BATHTUB can depict a segmented dendritic reservoir, a subregion of a reservoir, or several hydraulically connected reservoirs, as well as the simplest configuration of a single, horizontally well-mixed system. The model assumes a steady state, so the above parameters are usually taken to be averages over the time period addressed, typically the summer stratification period, but perhaps several replacement times (referred to in Walker, 1996, as "turnover rates") dependent upon the volume throughflow of the reservoir.

BATHTUB is basically a series of flux-accounting programs, to which the user supplies an array of data, and the model closes the volume or mass budget, the computed (signed) surfeit being attributed to non-monitored processes. For example, the volume budget requires inputs from the user of inflows, discharges, evaporation, precipitation and net reservoir volume change, from which is computed a "net loss term". Mass balances are based upon observed segment-mean concentrations (whose computation from data is facilitated by PROFILE), tributary loading rates (whose computation from data is facilitated by FLUX), and numerous options for quantifying kinetic transformations among variables. From a mass budget, surfeit values are used to estimate kinetic and sedimentation rates (by fitting empirical models to the observed relations). The user has a range of options, e.g. to explore different partitions of nutrient inflow loads with a constant sedimentation rate versus allowing variable sedimentation rates in the inflows. A conservative tracer is generally used to determine diffusive (a.k.a. dispersive) flux rates.

The ultimate purpose of BATHTUB is to provide a means of predicting eutrophication response to nutrient concentrations. The user can select from an array of "models" of chlorophyll-a dependency upon pool nutrient levels, each of which assumes a different subset of limiting factors among nitrogen, light and flushing time, in addition to phosphorus. Each "model" is a statistical relation developed from data from Corps reservoirs. Data analysis using FLUX and PROFILE guide the user in selecting among these models. Since the model is empirical, site-specific data can always improve (or perhaps replace) the built-in statistical relations, so BATHTUB includes capability to re-calibrate the statistical models if the user has available data from the reservoir of interest. There is also a capability to carry out sensitivity and error propagation analyses.

According to the WES documentation, the input data requirements for each of the three programs are:

FLUX - water-sample data and continuous (e.g., daily) flow records.

PROFILE - vertical profiles of water quality (principally temperature, conductivity and DO) collected at one or more sample stations throughout the period of interest.

BATHTUB - water inflows and nutrient loads from tributaries (which may in turn be related to watershed characteristics), discharges and surface fluxes of water in the lake, and lake/reservoir morphology (see above). Observed lake or reservoir water quality data from the study reservoir are desirable to calibrate the statistical relations.

The model produces concentrations of nutrients, algae (chlorophyll-a) and related parameters, averaged over each reservoir segment, in tabular and graphical formats.

Based upon the present literature survey there appears to have been limited use of BATHTUB, represented primarily by reports by its developer or by WES in the course of analyzing Corps reservoir projects, e.g. Kennedy (1995). This documentation is in the rubric of "gray" literature.

BATHTUB is designed for use on a PC platform, which is specified (Walker, 1996) to be a minimum of 286 processor with math co-processor and 3 M of hard-drive disk space. The model is operated from the DOS prompt: there does not appear to be a Windows version. The user is led through a series of input screens, in which data files are accessed and selections of various modeling alternatives are indicated. Model documentation and downloads are available on the WES Internet website:

http://www.wes.army.mil/el/elmodels/emiinfo.html or from the model distributor at WES, Dr. Robert H. Kennedy (kennedr@wes.army.mil). No information is available as to source language or access to source code.

Model: **CE-QUAL-ICM (3D Eutrophication Model)**

Source: Waterways Experiment Station
U.S. Army Corps of Engineers
3909 Halls Ferry Road
Vicksburg, MS 39180

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

streams and rivers
lakes and reservoirs
estuaries

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry	☑ yes	☐ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures exceed that of maximum density	☑ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☐ no

flexible in its licensing requirements ☐ yes ☐ no

capable of transporting to variety of PC platforms ☐ yes ☐ no

source code available to potential users ☐ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

CE-QUAL-ICM is one of the array of watercourse programs developed by the Waterways Experiment Station, originally intended for application to environmental problems encountered by Corps districts. The model is described in Cerco and Cole (1994). According to the WES website (see below), CE-QUAL- ICM has evolved from a 3D water quality model developed for Chesapeake Bay to evaluate the effectiveness of nutrient reduction proposals on Bay eutrophication. This model contains a bottom-sediment chemistry submodel that interacts with the water column for simulating sediment oxygen demand and nutrient fluxes (DiToro and Fitzpatrick, 1993). The CE-QUAL-ICM modeling approach involves first applying a 2D or 3D hydrodynamic model and coupling the output to CE-QUAL-ICM for driving the transport terms. The water quality model can then be applied for a variety of conditions without having to rerun the hydrodynamic model.

The CE-QUAL-ICM model is reported by WES to have been applied to several coastal systems, including Chesapeake Bay, the New York Bight, Lower Green Bay, Los Angeles - Long Beach Harbor, and Indian River - Rehoboth Bay. Two such reports were found in the literature survey, both by WES staff. Cerco and Cole (1992, 1993) present an application to eutrophication in Chesapeake Bay, in which CE-QUAL-ICM was driven by the 3-D Chesapeake Bay hydrodynamic model and was supplemented with a "benthic sediment diagenesis" model. Application was to a 3-year period, 1984-86, which served as calibration. The eutrophication process was modeled with 22 variables, including a physical group consisting of salinity, temperature, and TSS, a carbon-cycle including carbon fixation by three algal groups, a nitrogen cycle in which nitrate and ammonium are oxidized by the three algal groups, a similar phosphorus cycle, a silica cycle and a dissolved oxygen (DO) cycle. The authors report model-data agreement with the historical record to be inconclusive, but the model successfully simulated water-column and sediment processes, and further simulated the spring algal bloom driven by the annual peak in nutrient run-off, and the cycle in summer anoxia.

Mark et al. (1992) describe an application to Green Bay, Wisconsin, to evaluate possible impacts from expanding a dredge disposal site near the southern shore (Kidney Island). The model was used to examine spatial and temporal variations in dissolved oxygen (DO) concentrations between pre-expansion and post-expansion CDF configurations. The WES 3-dimensional curvilinear hydrodynamic model was calibrated and verified against water levels and current velocities in lower Green Bay. The model current field was then used to drive CE-QUAL-ICM, which included two sources (reaeration and algal photosynthesis) and five sinks (sediment oxygen demand, labile and refractory chemical biological oxygen demand, algal respiration, and nitrification) of DO.

Thus far the model appears to have had extensive application to only large estuaries or very large lakes. While no applications to rivers or smaller lakes/reservoirs are reported, the model geometry is derived from that of the hydrodynamic model, so it appears that if a suitable hydrodynamic model is on hand, CE-QUAL-ICM can be adapted to simulate the watercourse. It is also apparent that model operation is labor and data intensive, and there are numerous parameters that must be specified to complete the application. With so many parameters, most of which must be established by calibration, it is not clear how accurate the basic model formulation is.

The most important aspect of CE-QUAL-ICM is not the utility of this model *per se* to Texas TMDL determinations, but the fact that the kinetics from CE-QUAL-ICM (which is most of the model) have been incorporated into other models for specific watercourses, notably CE-QUAL-W2 for reservoirs, lakes and deep channel estuaries, and EFDC for estuaries and coastal bays. Additional discussion of the model kinetics is given in the context of each of these models.

Information about CE-QUAL-ICM is obtainable from the following Internet site:

http://www.wes.army.mil/EL/elmodels/w2info.html

Model: **CE-QUAL-RIV1**

Source: Waterways Experiment Station
U.S. Army Corps of Engineers
3909 Halls Ferry Road
Vicksburg, MS 39180

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Streams and rivers
Run-of-the-river-reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☑ yes	☐ no
streams dominated by fluvial-type bathymetry	☑ yes	☐ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☐ yes	☐ no
in public domain	☐ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☐ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

CE-QUAL-RIV1 is another of the array of watercourse programs developed by the Waterways Experiment Station, originally intended for application to environmental problems encountered by Corps districts. According to the WES website, CE-QUAL-RIV1, a one-dimensional, dynamic flow and water quality model for streams developed for engineering projects on major riverine systems. It was originally developed in 1982 (Bedford, Syckes, and Libicki, 1982), and can be used on riverine systems with highly unsteady flows as well as those with steady flows. It is capable of simulating branched riverine systems with multiple hydraulic structures, such as weirs, re-regulation dams, and navigation locks and dams. One of its original objectives was for application to the tailwaters of peaking hydropower dams.

CE-QUAL-RIV1 consists of two components, RIV1H and RIV1Q, the hydrodynamic module and water quality module, resp. RIV1H can be used as a stand-alone model, which simulates river flows, stage, depths, cross-sectional areas and top widths. RIV1Q can be de-coupled from RIV1H and be coupled to an external hydrodynamic model that provides all the necessary information to run. Therefore, a watershed model that can provide sufficient input information may be used to drive RIV1Q, and RIV1Q could model the instream processes and constituents. RIV1Q calculates time series of concentration for eleven different water quality parameters, including temperature, DO, CBOD, and the nitrogen cycle.

A few applications of CE-QUAL-RIV1 are reported in the literature, by WES personnel, all addressing the effects on water quality due to the regulation of streamflow by hydropower dams, the most recent application of which was the Missouri River in 1993. These sources appear to be confined to the "gray" literature.

No information about availability or licensing of CE-QUAL-RIV1 was found, and the primary contact at the USCE, Dr. Mark Dortch, did not respond to inquiries. Some limited information is given on the WES Internet site:

> http://www.wes.army.mil/EL/elmodels/w2info.html

Model: **CE-QUAL-W2**

Source:

Waterways Experiment Station
U.S. Army Corps of Engineers
3909 Halls Ferry Road
Vicksburg, MS 39180

Attention: Thomas M Cole (colet@wes.army.mil)

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

lakes and reservoirs
deep channel-type estuaries

Representative of Texas hydrological systems and Texas hydroclimates:

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures exceed that of maximum density	☑ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☐ yes	☑ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no

source code available to potential users ☑ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 4 - Criteria specific to special-purpose estuary models

(1) Model formulation

spatial depiction: ☐ one-dimensional longitudinal ☐ two-dimensional horizontal ☑ two-dimensional longitudinal-vertical ☐ three-dimensional

variable geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☑ time varying tidal-mean ☑ fully time varying

accommodates riverine hydrographs? ☑ yes ☐ no

includes gravitational circulation (density variation)? ☑ yes ☐ no

basis for current distribution: ☐ direct input ☐ continuity only ☐ separate hydrodynamic model ☑ integral hydrodynamic model ☐ other

water quality (mass transport) capability included? ☑ yes ☐ no

sediment dynamics in estuary included? ☑ yes ☐ no

peripheral sediment loads included? ☐ yes ☑ no

(2) Numerical solution

method for numerical specification of estuary geometry:
☑ manual input ☐ import of standard files ☐ grid generator ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

for hydrodynamic models with coupled density, scale separation or mode-splitting?
☐ yes ☑ no

(3) Implementation for computer operation

Source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

Minimum hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Has the model been routinely flanged with a watershed model? ☐ yes ☑ no

Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ☑ yes ☐ no

(4) Suitability for Texas estuarine systems.

Demonstrated application to bays or estuaries typical of Texas? ☐ yes ☑ no

Acceptable performance in model validation studies? ☑ yes ☐ no

Acceptable level of technical acceptance? ☑ yes ☐ no

(5) Capability for implementation in a GIS environment.

Has model been operated with GIS derived inputs, either with or without an associated watershed model? ☐ yes ☑ no

Has model output been displayed using modern visualization capabilities?
☐ yes ☑ no

Screening Level 4 - Criteria specific to special-purpose lake and reservoir models

(1) Model formulation

spatial depiction: ☐ one-dimensional longitudinal ☐ two-dimensional horizontal
☑ two-dimensional longitudinal-vertical ☐ three-dimensional

variable geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☑ fully time varying
☐ slowly varying (long term averaging, e.g. monthly)

accommodates riverine hydrographs? ☑ yes ☐ no

includes stratification (density variation)? ☑ yes ☐ no

basis for current distribution: ☐ direct input ☐ continuity only
☐ separate hydrodynamic model ☑ integral hydrodynamic model ☐ other

basis for vertical diffusivity: ☐ direct input ☐ constant
☐ turbulence sub-model in hydrodynamics ☑ other

heat budget and temperature capability included? ☑ yes ☐ no

ice formation included? ☐ yes ☐ no

water quality (mass transport) capability included? ☑ yes ☐ no

sediment dynamics in reservoir included? ☑ yes ☐ no

peripheral sediment loads included? ☐ yes ☑ no

(2) Numerical solution

method for numerical specification of reservoir geometry:
☑ manual input ☐ import of standard files ☐ grid generator ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

for hydrodynamic models with coupled density, any special treatment of vertical diffusivity terms?
☑ yes ☐ no

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

minimum hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

has the model been routinely flanged with a watershed model? ☐ yes ☑ no

(4) Suitability for Texas lake/reservoir systems.

Demonstrated application to lakes/reservoirs typical of Texas? ☑ yes ☐ no

Acceptable performance in model validation studies? ☐ yes ☐ no

Acceptable level of technical acceptance? ☑ yes ☐ no

Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ☑ yes ☐ no

Does model coding/input allow accommodate alternative reservoir operation rules? ☑ yes ☐ no

power-plant heat loads? ☑ yes ☐ no

(5) Capability for implementation in a GIS environment.

Has model been operated with GIS derived inputs, either with or without an associated watershed model? ☐ yes ☑ no

Has model output been displayed using modern visualization capabilities? ☐ yes ☑ no

Discussion

CE-QUAL-W2 is yet another of the array of watercourse programs developed by the Waterways Experiment Station, originally intended for application to environmental problems encountered by Corps districts. This is a 2D laterally averaged hydrodynamic and water quality model, designed for application to watercourses with prominent longitudinal variation that are deep enough for density stratification to be important (Cole, 1994). It was developed from a model of temperature-structure in a power-plant cooling water reservoir created by John Edinger and Ed

Buchak, LARM (for Laterally Averaged Reservoir Model), which they later adapted to the density-current circulation in a longitudinal estuary. LARM is essentially hydrodynamic, but with a variable density that is governed by water temperature (and in the case of the estuary, salinity) and the model includes heat budget terms in the temperature part of the solution. Edinger and Buchak then enhanced the model to include dendritic physiography, by a system of linked one-dimensional reaches, and reservoir operations.

WES added complex dissolved oxygen and nutrient budgets to the mass-balance part of the model, including the ability to simulate algae blooms. The kinetic terms are basically those developed for the Chesapeake and coded in CE-QUAL-ICM. The water quality algorithms incorporate 21 constituents in addition to temperature, including nutrient/ phytoplankton/ dissolved oxygen (DO) interactions during anoxic conditions. Any combination of constituents can be simulated. The effects of salinity or total dissolved solids/salinity on density and thus hydrodynamics are included only if they are simulated in the water quality module. The water quality algorithm is modular, allowing constituents to be easily added as additional subroutines if the user desires. The present version tracks separately the concentrations of organic material in both dissolved and suspended forms, and labile and refractory, all of which require various kinetic inputs from the user. The model has a limited capability for addressing sediment, being limited to one component of sediment and one user-specified settling rate. Also, the organic nutrients are not independent but limited by the Redfield ratio of N:P = 8:1. A new version of the model is in preparation that will allow more than one group of algae to be simulated.

Despite the "user friendly" objective of the structured, commented code and the substantial users manual, model set-up and execution are difficult. The WES website offers a "word of caution to the first time user," that model application is a complicated and time consuming task. Furthermore, the model has had relatively few applications in the recent literature, despite its being extant for almost 20 years, and many parts of the code have not been adequately tested.

Hayes et al. (1994) applied CE-QUAL-W2 to Douglas Reservoir for TVA, where the concern was the low DO in reservoir releases. The temperature and DO structure of the reservoir was simulated, and a selective withdrawal strategy was developed. Conservative tracers were injected at three locations in the model simulation to predict the possible trajectory of metals concentrations derived form bed sediments. Hayes et al. (1994) found the calibrated model to provide "a reasonable characterization of temperature and water quality conditions within the reservoir." They used computer animation to facilitate visualization of the model results (Shiao et al. 1994). Easley et al. (1994) gave a preliminary report on the application of the model to Taylorsville Lake in the Upper Salt River Basin, Kentucky, to determine the effects of erosion and nutrient controls. They state that CE-QUAL-W2's use of inflow, outflow, and meteorological data, as well as detailed bathymetry obtained from digitized mapping, can "closely simulate lake behavior," apparently in reference to time-space detail capability, rather than to actual validation.

Adams et al. (1997) applied CE-QUAL-W2 to the problem of evaluating the impacts of combined sewer overflows on Cheatham Lake, on the Cumberland River below Nashville. Severe DO deficits have been reported in the reservoir from time to time. CE-QUAL-W2 was calibrated and verified with 36 months of data, including 12 months of intensive monitoring and continuous data collection, and the predicted DO values were found to deviate no more than 1.0 mg/L from measurements. (The sewer overflows were exonerated as a cause of degraded DO.) A recent application of the model to Isikli Reservoir of the Ankara Water Supply System, Turkey, is described by Guenduez et al. (1998). Various water control strategies were examined, but since Isikli Reservoir is a proposed system, the model application is hypothetical.

An illustration of the potential problems stemming from the complexity of the model and the difficulty of properly implementing it is given by recent (and ongoing) attempts to model Brownlee Reservoir, a run-of-the-river hydroelectric reservoir on the Snake River, Oregon (Kingery and Harrison, 1997, Harrison and Anderson, 1997). In this application, data on temperature and DO structure from two summer seasons (1992 and 1995) were used to calibrate the model, but there was no verification against DO data. Further, the only hydrodynamic verification was to check the volume budget (which amounts to checking the magnitudes of gauged inflows in the river and gauged releases through the dam). The comparison of model and measurement of temperature was not very good, and it was reported that the model was rather insensitive to the calibration variables for hydrodynamics so the temperature prediction could not be improved (Kingery and Harrison, 1997). For DO, the model prediction compared to observations proved even worse. The model does not replicate the observed DO structure satisfactorily (failing to predict two substantial reaches of below-standard DO that occur in the reservoir). The model produces features in the computed DO structure that are clearly erroneous, *viz*. a large volume of near-saturation DO at thermocline level at the dam. These anomalies appear to arise, not from deficiencies in information about the DO sources/sinks, but from deficiencies in the hydrodynamic fluxes.

At present the Tarleton Institute for Applied Environmental Research (TIAER) is applying CE-QUAL-W2 to Lake Waco. This effort has required over a person-year for model learning-curve and set-up of the input files, i.e., to enable model executions to be routinely made. The main emphasis of the TIAER work is in simulating nutrients and algae, but this requires that some attention be given to DO. Lake Waco was depicted as three branches: (1) main branch, including dam, (2) north arm of reservoir, including inflow from North Bosque, and (3) south arm of reservoir, including inflows from Middle and South Bosque. Each branch was discretized into segments of approximately 500 m length, with a vertical increment (layer thickness) of 1 meter, resulting in a computational grid of 47 longitudinal segments by 37 layers. Computational stability of the model is controlled by the built-in "autostepping" process, in which the next timestep is computed so as to enforce the Courant condition. For the Lake Waco simulations, these time steps ranged from 1 second to 60 minutes, averaging around 10 minutes.

In the process of early calibration, bugs in model kinetics had to be ferreted out of the FORTRAN and corrected. Also, TIAER discovered an inconsistency in the water balance, that the precipitation influx is computed using a different segment surface width (for the surface area) from that used for evaporation. This work is underway: preliminarily, the model temperature profiles are comparing well to observations (Lake Waco is too shallow to have a hypolimnion form in the summer, however), but there remain problems in the predicted DO's with respect to observed oxyclines in the deeper sections of the lake, now being addressed by TIAER (Flowers, pers. comm., 1999).

The current version of the model is written in FORTRAN. The model will execute on a PC platform, but it is computationally intensive and will require long execution times for simulations of any appreciable calendar duration. Information about the model is available from the WES Internet site:

http://www.wes.army.mil/EL/elmodels/w2info.html

The model itself and the associated documentation cannot be downloaded from this location, but can be obtained by anonymous ftp by contacting the model distributor at WES.

Model: **CHARIMA**

Source: Iowa Institute of Hydraulic Research
The University of Iowa
404 Hydraulics Laboratory
Iowa City, Iowa 52242-1585

1. Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Rivers and streams
Estuaries and coastal waters

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☐ yes	☑ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☑ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

CHARIMA is a one-dimensional nonsteady hydrodynamic model developed by Forrest Holly at IIHR. The model is a numerical solution to the complete St. Venant equations, and is limited to subcritical flows, hence probably cannot treat extreme flood hydrographs, but otherwise is quite general. Emphasis of the model is sediment dynamics, but the model can also be used to trace the concentration of a conservative parameter or heat. A later version of the model will include nutrient and DO kinetics as an option.

The model is best characterized as a research tool, and is not available for general public release. Consequently, it was given no further study in this review.

Model: **CLAWS (Coupled Landscape and Water System)**

Source: Under development, Lawrence Livermore Laboratory

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
streams and rivers

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☐ yes	☑ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

CLAWS is a watershed/basin model under development at the Lawrence Livermore National Laboratory of the University of California. The basic program is written in ANSI C and is designed for PC and UNIX platforms. The model couples hydrological and geomorphic processes for complex terrain described by digital elevation data. The model is process-based and distributed.

Input data include precipitation, temperature, solar radiation, soil and vegetation. The model emphasizes forested landscapes and includes forest distribution and logging history. Vegetation dynamics is one component of the model, for which parameters include biomass, tree height, cover density, leaf area index, and root strength. The model also addresses snowpack, melting and accumulation, and landsliding. Subsurface water movement is based slope-parallel saturated flow through a limited depth of soil. No literature publications describing application of CLAWS were found.

Information about CLAWS is provided on the following Internet web site:

http://www.hydromodel.com/duan/claws/claws.htm

Model: **CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems)**

Source: Agricultural Research Service
U.S. Dept. of Agriculture
Grassland, Soil & Water Research Laboratory
808 East Blackland Road
Temple, TX 76502

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds (field-scale catchments)
vadose zone (root zone)

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic	☑ yes	☐ no

Level-1 Screening:	☑ **eliminate**	☐ **consider**

Discussion

The CREAMS model dates back to the 1970's, and was one of the early models of the Soil Conservation Service developed to predict runoff and waterborne loads from agricultural areas (Renard, 1993). Its purpose was to perform long-term simulations using a daily time step, and in this respect differs from "event" models such as ANSWERS. The spatial depiction of CREAMS is limited however; it is a "field" model, meaning that the land surface is assumed to have (1) a single land use, (2) relatively homogeneous soils, (3) spatially uniform rainfall, and (4) a single management practice. The hydrology of the model is based upon the SCS curve-number method (Knisel and Williams, 1995), though there is an option to use the Green-Ampt infiltration equation. The sediment mobilization and transport is strongly based upon the USLE philosophy, with only slightly modified USLE equations. The greatest strength of the model is explicit representation of nutrient kinetics and their interaction with cropping. The nitrogen kinetics includes expressions for mineralization, nitrification, and denitrification processes, plant uptake and leaching out of the root zone. The model has been extended to computing pesticide loss, hence pesticide loadings (e.g., Neary et al., 1993). The pesticide kinetics include expressions for foliar interception, degradation, and washoff, as well as adsorption, desorption, and degradation in the soil.

Because of its 25-year history, numerous applications have been made of CREAMS. Comparisons with observations seem to be in the minority. Cooper and Bottcher (1993) applied the model to a 73-km^2 watershed in New Zealand, and found the model to predict almost exactly the 14-year mean runoff, while the average sediment and nutrient loads were "generally within 30%" of observations. They found the model predictions of nutrient loading to be sensitive to stream attenuation coefficients. The performance of the model on shorter time frames was not as good but still characterized as "moderately strong" for hydrology and "unbiased" for N and P losses (Cooper et al., 1992).

Use of the curve-number method has been identified by some workers as a fundamental weakness of the model (shared by models of similar hydrology, such as EPIC and AGNPS). McCool et al., (1995), for example, determined runoff curve number relationships from runoff plot data from the Palouse Conservation Field Station near Pullman, Washington. They found these measured values to range considerably higher than curve numbers commonly used.

Wagner and Roesner (1993) and Wagner et al., (1996) adapted CREAMS (together with QUAL2E as the receiving water transport model) for modeling phosphorus loading from the Lake Okeechobee watershed, and report good agreement of the computed phosphorus loads with observations. See also Zhang et al. (1995) for comparative evaluations of CREAMS and another watershed model. Bingner et al. (1989) carried out a comparison of CREAMS, ANSWERS, SWRRB, EPIC and AGNPS using data from Mississippi research watersheds, and found CREAMS and SWRRB to produce results "close to" measured values more than the other models. Wu et al., (1993) report an evaluation of CREAMS, along with ANSWERS and AGNPS, using data from 30 runoff events on three experimental watersheds. They found the modeled runoff to show "reasonable to poor agreement" with field data, and "large scatter" in ratios of computed to measured sediment yields. All models were found to underpredict sediment loading for large storms.

Rekolainen and Posch (1993) made many modifications to the model, including incorporation of snow accumulation processes, plant growth, and variable rainfall erosivity parameters, and report improved performance of runoff and soil erosion. Evans et al. (1994) used laboratory rainfall simulator data to determine interrill erodibility parameters for

CREAMS. They found their derived parameters varied with slope, indicating that the slope gradient response predicted by CREAMS may not be applicable for interrill erosion on short, steep slopes.

Many applications in the literature use CREAMS as the basic model for landscape processes in an agricultural setting, reporting comparative studies, or employing the CREAMS output in a project of larger scope. Among these qualitative studies, Diebel et al. (1992) used CREAMS in concert with an economic model to evaluate alternative policy scenarios, including cost sharing for green manures, restrictions on atrazine application levels, chemical taxation, restriction on potential chemical and nitrogen levels in surface and groundwater, and land-retirement programs. Hamlett and Epp (1994) and Epp and Hamlett (1996) similarly used CREAMS together with economic calculations to compare conservation BMP strategies, both nonstructural (no-till, contour, contour with waterways, strip crop with waterways, filter strips) and structural (terraces, tile outlet terraces, sediment basins). Giraldez and Fox (1995) used CREAMS to evaluate the economic benefits to controlling nitrate application thus reducing groundwater contamination. Williams and Nicks (1993) used CREAMS to evaluate the effectiveness of filter strips.

low-relief terrain, semi-arid to subhumid basins	☑	yes	☐	no

Model: **DESERT (DEcision Support system for Evaluation of River basin sTrategies)**

Source: Under development, International Institute for Applied System Analysis (Austria)

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
streams and rivers

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑	yes	☐	no
basins dominated by fluvial drainageways	☑	yes	☐	no
substantially altered hydrology due to storage and conveyance systems	☐	yes	☑	no
substantially altered hydrology due to urbanization	☐	yes	☑	no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐	yes	☑	no
streams dominated by fluvial-type bathymetry	☑	yes	☐	no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑	yes	☐	no
in public domain	☑	yes	☐	no
flexible in its licensing requirements	☑	yes	☐	no
capable of transporting to variety of PC platforms	☑	yes	☐	no
source code available to potential users	☑	yes	☐	no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

DESERT is an integrated PC-based river-basin modeling system under development by International Institute for Applied System Analysis (IIASA), Laxenburg, Austria, in cooperation with the Institute for Water and Environmental Problems, Barnaul, Russia. IIASA promises a data handling module, simulation and calibration of hydraulics and water quality, display of computed data "with the help of external spreadsheet software", and optimization based on dynamic programming The purpose of the software package is "providing a useful and powerful instrument for water quality assessment and decision making", including selection of wastewater treatment alternatives, establishing water quality standards, and enforcement. No reports of applications could be located in the literature. (Three "gray-literature" citations are given on the following home page.)

Additional information is available at the Internet site:

http://www.iiasa.ac.at/Research/WAT/docs/desert.html

Model: **DR3M (Distributed Routing Rainfall-Runoff Model)**
DR_3M-QUAL (Multi-Event Urban Runoff Quality Model)

Source: U.S. Geological Survey
Hydrologic Analysis Software Support Program
437 National Center
Reston, VA 20192

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☑ yes	☐ no
substantially altered hydrology due to urbanization	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

DR_3M is a node-channel depiction of a drainage network including an option for detention storage in node definition, developed by the U.S. Geological Survey. Segments can be channel or "overland", the latter including a surface water budget (infiltration, evaporation, soil moisture accounting) to compute excess rainfall, which is carried to the next segment according to surface slope, resistance and fraction of impervious cover.

The excess rainfall computation is based upon work of Dawdy et al., (1972). The resulting flow is applied as uniform lateral inflow to a channel segment. The channel segments utilize a kinematic-wave routing approach, adapted from LeClerc and Schaake (1973). Segment specification can include pipes and culverts as well as natural channels. The water-surface profile must be supplied from another model (WSPRO). Detention at a node is specified by a storage constant T (dimensions time), used in computing stored volume as $V = QT$, where Q is the outflow from the "reservoir" node. The outflow-storage relation is derived from WSPRO runs.

Few applications are reported in the literature, and these are entirely "gray" literature. Baker (1987) applied the model to evaluation urbanization effects on floods from a Baton Rouge bayou basin, but does not appear to have evaluated the performance of the model. Good agreement was found between model and observations of discharge from urban flood-detention reservoirs in watersheds in Albany GA (Hess and Inman, 1994). Application to the flashy urban watershed of

Bear Branch in Murfreesboro TN (Outlaw, 1996) yielded SEE's of runoff at two USGS gauges of 54% and 98%.

DR3M is purely a hydrologic model designed for evaluating watershed impacts typical of urbanization on peak discharges and flood. The intended application is to "small urban watersheds." DR3M-QUAL is apparently an adaptation of DR3M, adding capability for pollutant transport. No applications for this version of DR3M could be found in the literature review.

The model may be downloaded from the USGS Internet site:

http://water.usgs.gov/software/dr3m.html

and via anonymous File Transfer Protocol (ftp) from:

water.usgs.gov (path: /pub/software)

The last major re-write of the model was promulgated in 1984. The latest modifications noted to the model were some rather minor I/O changes in 1991.

Model: **DYNHYD (Dynamic Hydrodynamics Program)**

Source: Environmental Protection Agency
Center for Exposure Assessment Modeling
960 College Station Road
Athens, GA 30605-2700

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Rivers and streams
Estuaries and coastal waters
Reservoirs and lakes

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☑ yes	☐ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☑ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution ☑ yes ☐ no

in public domain ☑ yes ☐ no

flexible in its licensing requirements ☑ yes ☐ no

capable of transporting to variety of PC platforms ☑ yes ☐ no

source code available to potential users ☑ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria for stream/river models

(1) Model formulation

variable channel geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☑ time varying

accommodates flood-type hydrograph? ☑ yes ☐ no

basis for current computation: ☐ direct input ☐ continuity only ☐ kinematic wave ☑ complete hydraulic model ☐ other

water quality (mass transport) capability included? ☐ yes ☑ no sediment dynamics in stream included? ☐ yes ☑ no

peripheral sediment loads included? ☐ yes ☑ no

capability to include channel estuaries? ☑ yes ☐ no

run of river reservoirs? ☐ yes ☑ no

(2) Numerical solution

method for numerical specification of stream channel and network:
☑ manual input ☐ import of standard files ☐ GIS

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

minimum hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

has the model been routinely flanged with a watershed model? ☐ yes ☑ no

Level-2 Screening: ☐ **eliminate** ☑ **consider**

Discussion

DYNHYD (current version DYNHYD5) traces its origin to the Orlob-Shubinski estuary model of the 1960's, originally developed for San Francisco Bay, whose best-known East Coast applications are the EPA Potomac and Delaware models (see Ward and Espey, 1971). DYNHYD is a link-node hydrodynamic model simulating velocity, volume, and water depth under river flow and changing tidal phenomena. The equations of conservation of mass and energy are solved by the method of finite-differences to predict water velocities, flows, water heights, and volumes. The model is driven by variable upstream flows and downstream heads and assumes that flow is predominantly one-dimensional (i.e., Coriolis and other accelerations normal to the direction of flow are negligible). Bed characteristics are parameterized using

Manning’s *n*. Wind that can either oppose or concur with flow can also be accounted for within the model.

Technically, DYNHYD is a one-dimensional model, simulating velocity in the direction of the channel, but is applied to two-dimensional (vertically integrated) systems by approximating the system by a network of nodes with interconnected one-dimensional channels. A system like San Francisco Bay is therefore depicted as an array of storage tanks connected by water troughs. It is also only a hydrodynamic model with no capability for simulating the transport of a waterborne constituent. It is generally operated in conjunction with a transport (i.e., water quality) model lacking a hydrodynamic capability. For the EPA model WASP, DYNHYD is the companion hydrodynamic model.

Input data for DYNHYD include the following:

- initial surface elevations, bottom elevations and segment volumes;
- channel lengths, widths, areas, roughness, orientations, and initial velocities;
- variable or constant boundary flows;
- downstream boundary surface elevations and
- wind parameters.

Experience has shown that it best to have the downstream boundary be located at a point where measurements are available (i.e. flow or stage height gauge). In addition, in most applications of DYNHYD5, Manning's roughness coefficient has been the primary calibration parameter (Ambrose, *et al.*, 1993).

The model assumes a simple channel geometry, that channels are rectangular in cross section and therefore cross sectional area is proportional to depth. Thus this sort of model would not be appropriate for applications to rivers with floodplain areas or gentle lateral side slopes. The geometrical depiction of a two-dimensional watercourse as a network of interconnected tanks can be misleading, as pointed out by many modelers, for example Fischer et. al (1979) state, “If the nodes are laid out in a line along a channel the hydraulic properties are those of the real channel; if the nodes are arrayed to represent a bay fictional hydraulic properties of the links must be invented…. The distribution of nodes in a bay can define the equivalent of a two-dimensional grid, although the program is not truly two dimensional because flow is permitted only in the direction of a link." The numerical method is an explicit finite-difference method (Ambrose and Martin, 1993). This method is conditionally stable, with the familiar Courant condition that the time step is limited by the speed of propagation of free surface waves. As an example, the time step used by Cusimano (1995) was 60 seconds.

Generally, DYNHYD5 cannot be applied to stratified water bodies or water bodies without well-defined primary flow directions. Therefore it is not the model of choice for broad estuaries and large lakes, unless the environmental regime of interest is greatly simplified. In lakes the primary flow directions are generally not well defined *a priori*, and large estuaries are usually stratified in some regions during some periods. In addition, vertical mixing processes are very important to the dynamics of lakes and large estuaries and these cannot be modeled using a one-dimensional model. DYNHYD5 has been applied to compute flows in some estuaries, however the velocity field output by DYNHYD5 does not resolve all the important mechanisms of mixing. Therefore, in order to compute transport of contaminants in estuaries, large dispersion coefficients must be estimated (e.g., Cusimano, 1997). DYNHYD can be employed usefully to modeling the tidal reach of a river.

The more usual configuration for DYNHYD is a steady or slowly varying inflow regime, for evaluation of critical-condition or normal-condition water quality. Since DYNHYD is a time-advancing model, in principle it can handle dynamic events, such as flood hydrographs. However, its limited accuracy would probably result in poor accuracy for a "fully dynamic event" such as a flood event in a flashy stream. The rectangular geometry assumed for the interconnecting channels and the lack of a floodplain capability would render DYNHYD5 inappropriate for many streams. So long as the hydrograph remains within the stream channel banks and the stream cross section is flat-bottom with steep banks, DYNHYD would be appropriate. Certain dynamic hydraulic conditions, such as dam-break situations or flow in small mountain streams (i.e. steep, low flowing streams), which require more accuracy in the hydraulic stress terms, cannot be simulated using DYNHYD. A dynamic flood event will, we note, impose a significant input-file handling challenge for the model user.

The greatest attraction of DYNHYD is its relative simplicity of operation. The model code is transparent and easily adapted to the needs of the user. The model is configured completely by modifying input files. Linkage to WASP5 and EUTRO5 is achieved by saving DYNHYD5 output in electronic files. Because a small number of nodes is generally used with DYNHYD5, the grid specification is less time intensive than most two- or three-dimensional models. Input requirements of DYNHYD5 are fairly minimal. The user's manual (Ambrose et al., 1993) outlines all input data in 16 pages of text. Inputs include various forms of geometry data specifying the surface area and depth of each node, the node numbers bounding each link, the length of each link, etc. Initial and boundary conditions including the initial head of each point and inflows are also specified in the input files. Probably the most difficult and time consuming step of preparing model input for a coupled DYNHYD5/WASP5 simulation is computation of appropriate dispersion coefficients.

Because DYNHYD5 is usually coupled with WASP5, the model has been widely used in a variety of projects. Morton et al. (1989) applied DYNHYD4 and WASP4 to modeling eutrophication in the embayments of the Peconic estuary of Long Island, New York, a concern created by the brown tide bloom of1985-88. Data from 1976 was used for calibration for CBOD, nutrients, chlorophyll, salinity and oxygen. EUTRO4 used the WASP4 output. Recently the USEPA supported a TMDL case study that used DYNHYD5 to model the Appoquinimink River in Delaware (Morton, 1994). Other studies included the modeling of Oso Bay in Texas (Hussain, 1995), the simulation of organic chemicals in the Delaware Estuary (Ambrose, 1987), modeling of toxics and nutrients in Galveston Bay (Clarke et al., 1993), and the modeling of Snohomish River Estuary (Cusimano, 1995, 1997). The last application involves an extensive deltaic channel area adjacent to the estuary, for which the link-node geometry of DYNHYD was very appropriate. Koh et al. (1993) describe an application to modeling BOD-DO in the Johor River estuary, Malaysia. Tidal flows were simulated with DYNHYD5, and WASP5 was used with agricultural and industrial loadings.

Besides WASP, no other documentation was found discussing linkages of DYNHYD to other models of water-quality parameters. The only documented case found in which DYNHYD was integrated into a GIS framework was by DiPinto *et al.* (1994). This study used ArcInfo to develop a user interface (GEO-WAMS), which integrated EPA's WASP4 and DYNHYD5. In this study, GIS was used to segment to river, develop the boundary and initial conditions, determine the model parameterization, write the input file, run the model, and display the output. The input to DYNHYD that is most easily facilitated by GIS is segment length. Other input such as initial head, and channel geometry can be stored in GIS via attribute tables, but GIS is not vital in their determination. Because DYNHYD is purely hydrodynamic (i.e. no water quality component), the input of watershed loadings is not necessary; however, the linkage to the runoff calculations by a watershed model would be important.

The DYNHYD program and documentation are not supplied separately by CEAM, but are included as part of the WASP modeling system, downloadable from the CEAM Internet site:

ftp://ftp.epa.gov/epa_ceam/wwwhtml/wasp.htm

The model is coded in FORTRAN and is executed under DOS (in the current version). In many respects, DYNHYD is a throwback to the 1960's when computer resources were limited and input files had to be manually assembled from punched cards. Its mode of operation, for example, follows the "batch" execution philosophy. Several companies market commercial versions of DYNHYD that operate from a WINDOWS interface, such as

AScI Corporation
1365 Beverly Road
McLean, VA 22101

The utility of DYNHYD for TMDL determination in Texas is considered to be confined to those situations in which the modeling problem favors simplicity and expediency in set-up and execution, when the WASP system may offer a useful approach. (While DYNHYD is disseminated with the WASP model as a standard hydrodynamic input, WASP can be applied with other, more rigorous hydrodynamic models, although some re-formatting may be necessary.) DYNHYD may be considered a viable candidate as a hydrodynamic model if (1) transport by currents is considered to be less important than kinetics for the constituent and watercourse of concern, (2) the geometry of the watercourse is simple and favors a link-node depiction, e.g. interconnected branching channels, or a tidal river.

Model: **DYNTOX (Dynamic Toxics Model)**

Source: Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
Environmental Research Laboratory
College Station Road
Athens, Georgia 30613

Screening Level 1 Criteria

The available information proved inadequate to complete a Level-1 screening.

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

EPA bills DYNTOX as a "Dynamic Toxics Waste Load Allocation Model" and documents it in a 1985 user's manual. It was designed to compute the impact of toxic discharges on receiving water quality, under both steady state and dynamic conditions, for the purpose of wasteload allocation. Part of the model capability is statistical, evaluating frequency and duration of exposure above specified limits, evidently through a Monte Carlo procedure. The web page (see below) states, "new features of the model include partial mix factors and variable water quality criteria for metals and ammonia." No literature citations could be found documenting the application of the model.

Limited information about DYNTOX is available from the EPA Internet site:

http://www.epa.gov/OWOW/watershed/tools/model.html#5

and from the CEAM site:

www.epa.gov/CEAM

Although DYNTOX is listed as "supported" by CEAM, we could locate no download access to this model.

Model:	**EFDC (Environmental Fluid Dynamics Code)**
Source:	Environmental Protection Agency Center for Exposure Assessment Modeling U.S. Environmental Protection Agency Environmental Research Laboratory College Station Road Athens, Georgia 30613 Also: School of Marine Science, Attn: Mac Sisson Virginia Institute of Marine Science The College of William and Mary Gloucester Point, VA 23062

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Estuaries, coastal ocean, lakes, reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 4 Criteria specific to special-purpose estuary models

(1) Model formulation:

spatial depiction: ☐ one-dimensional longitudinal ☐ two-dimensional horizontal ☐ two-dimensional longitudinal-vertical ☑ three-dimensional

variable geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☐ time varying tidal-mean ☑ fully time varying

accommodates riverine hydrographs? ☐ yes ☐ no

includes gravitational circulation (density variation)? ☑ yes ☐ no

basis for current distribution: ☐ direct input ☐ continuity only ☐ separate hydrodynamic model ☑ integral hydrodynamic model ☐ other

water quality (mass transport) capability included? ☑ yes ☐ no

sediment dynamics in estuary included? ☑ yes ☐ no

peripheral sediment loads included? ☐ yes ☐ no

(2) Numerical solution:

method for numerical specification of estuary geometry:
☐ manual input ☐ import of standard files ☑ grid generator ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

for hydrodynamic models with coupled density, scale separation or mode-splitting?
☑ yes ☐ no

(3) Implementation for computer operation

Source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

Minimum hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Has the model been routinely flanged with a watershed model? ☐ yes ☐ no

Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ☑ yes ☐ no

(4) Suitability for Texas estuarine systems.

Demonstrated application to bays or estuaries typical of Texas? ☐ yes ☑ no

Acceptable performance in model validation studies? ☐ yes ☐ no

Acceptable level of technical acceptance? ☐ yes ☑ no

(5) Capability for implementation in a GIS environment.

Has model been operated with GIS derived inputs, either with or without an associated watershed model? ☑ yes ☐ no

Has model output been displayed using modern visualization capabilities?
☑ yes ☐ no

Discussion

The Environmental Fluid Dynamics Code, which originated at the Virginia Institute of Marine Science in Gloucester Point, VA, was developed fairly recently. The original Virginia Institute of Marine Science publications documenting the code were released in May of 1992 (Hamrick, 1992, 1996). The principal developer of EFDC, John Hamrick, is now at Tetra Tech, Inc.

EFDC is a three-dimensional hydrodynamic model, which has been applied primarily to study estuarine hydrodynamics (e.g. Shen *et al.,* 1997), but can also be applied to simulate hydrodynamics of the coastal ocean, and similar semi-enclosed bights. It is stated in the Users Manual (Hamrick, 1996) that the model can be "easily" reconfigured to depict two-dimensional systems, either laterally or vertically averaged. (If the model is applied to a one-dimensional system, i.e. a section-mean configuration, then the channel cross section is taken as rectangular. However, EFDC is not an appropriate choice for one-dimensional simulations.) Therefore, in principle, the model should be applicable to lakes, reservoirs, and deep channel estuaries, though no such applications could be located in the literature, except for Lake Okeechobee cited in Hamrick (1996).

In addition to the configuration of the estuary and the distribution of depths at each node in the computational network, inputs of either flows or water surface elevations are specified on the model-domain boundaries. A riverine system is specified in EFDC on an orthogonal curvilinear grid. Therefore the river is represented by a number of quadrilateral cells covering the area of the river. These quadrilaterals do not overlap and are arranged such that a line drawn between the centers of two adjacent cells approximately passes through the center of the side separating the two cells. The numerical method can handle rivers with floodplains if certain model options are used. It can also handle “sub-grid scale channels” (Hamrick, 1996) in which a channel cell is embedded in a larger floodplain cell.

Bed characteristics affect the bottom friction computed in simulations with EFDC. Bed characteristics are handled by a the "roughness length" z_o measuring the zero-shift of the near-bed logarithmic profile, generally considered to be proportional to the roughness elements of the bed, but in more complex flows can include the stress due to form drag of bedforms. The roughness parameter z_o can be set individually in each grid cell (Hamrick, 1996). EFDC also includes a capability to account for drag caused by vegetation (Hamrick, 1996).

Dispersion may be parameterized in EFDC by using a constant mixing coefficient (Hamrick, 1996). However, because EFDC is a three-dimensional model, it can resolve most of the relevant mixing mechanisms in rivers and estuaries if adequate grid resolution is used. Therefore, the dispersion coefficient used with EFDC should be small and representative of unresolved "sub-grid scale" mixing.

Transport of both cohesive and non-cohesive sediment can be modeled using EFDC. The parameters that need to be specified to model sediment transport include (Hamrick, 1996):

- Initial sediment in fluid phase
- Initial sediment mass per unit area of bottom surface
- Sediment specific volume
- Sediment specific gravity
- Constant or reference sediment settling velocity
- Two parameters used in a concentration dependent settling equation
- Four parameters used in a cohesive sediment resuspension equation
- One parameter used in computing bed elevation changes from sediment fluxes at the bed

All of these options are specified in input files. Because a large number of options are available, a good deal of expertise is required to set up the model to do sediment transport.

EFDC is one of the "new family" of very general, hydrodynamically based three-dimensional coastal models that have begun appearing within the last decade, a consequence of the great strides in computing power and the hunger for dissertation topics. Other examples include FIST3D (for Filtered in Space and Time, e.g. Rosman, 1989, Scudelari et al., 1997) and

QUODDT (Werner et al., 1994, Lynch et al., 1996). The best established of this "new family" of hydrodynamic models is the popular Princeton Ocean Model, POM (Blumberg & Mellor, 1987), and it is useful to compare EFDC to POM. Both models solve the governing hydrodynamic equations, *viz*. momentum and volume conservation equations. In addition, both use the Mellor-Yamada level 2.5 turbulence closure scheme to compute vertical mixing coefficients (eddy viscosity and eddy diffusivity). In both models orthogonal curvilinear horizontal coordinates are used and sigma (stretched) coordinates are employed in the vertical. The numerical methods of EFDC and the Princeton Ocean Model (POM) are also similar. The use of orthogonal curvilinear horizontal coordinates, as opposed to rectangular grid cells, allows the user some flexibility in generating model grids to fit the boundaries of the waterbody. In addition, both models use a mode-splitting technique in which the depth-averaged currents are solved in the “external” mode and vertical shears are computed in the “internal” mode.

The principal differences between EFDC and POM are:

(1) EFDC incorporates a mass-transport submodel, so that constituent distributions can be obtained as part of the model run;

(2) The model boundary specifications are more general and allow a wider range of options than POM. The above-noted river/floodplain depiction is one example. Another is that EFDC can be used in simulations with wetting and drying of computational cells, thereby being applicable to estuaries with shallow marshes or tidal mudflats that are exposed and inundated on the tide cycle.

(3) I/O routines are incorporated into the model to facilitate grid generation and to display model results.

The model can include the effect of wind waves on bottom stress in simulations, a wide variety of boundary conditions can be applied, various numerical methods for transport can be selected, and vegetation resistance can be included in hydrodynamic simulations without modification of the source code (Hamrick, 1996). The model includes a Lagrangian tracking submodel that can be used to simulate instantaneous releases of a conservative tracer, e.g. a spill of oil or hazardous substance, a dye release, or a discharge plume. The above noted capability for simulating wetting and drying of computational cells, which allows rudimentary modeling of wetlands, also includes a simplified soil water-budget Other differences between EFDC and POM include a greater range of options in the numerical solution of the equations, and (in principal) more precise, higher-order procedures. For example, in the solution of the advection-diffusion equation for transport of waterborne constituents the advection terms can be either first-order upwind or the MPDATA method of Smolarkiewicz and Clark (1986).

These and other options, though extraneous to most simulations, can be highly useful or even necessary for some specific projects. However, they also significantly increase the complexity of preparing model inputs and increase the probability that incorrect or incompatible options will be chosen by model users. Moreover, these increase the computational demands for executing the program, even if most of the options are disabled. To give some idea of the degree of complexity of this model, the user's manual for EFDC has 133 pages of text describing only model inputs and outputs (Hamrick, 1996).

In order to run EFDC a non-orthogonal curvilinear grid must be generated. Grid generation software is available with EFDC (Hamrick, 1996). In addition to grid generation many input files must be created. The setup of physically correct and compatible options with EFDC is expected to be unusually time consuming and difficult due to the number of options (frequently extraneous) that are available. However, modification of source code should not be necessary in most cases.

In addition to hydrodynamic modeling capabilities, EFDC includes sediment transport and heat-budget calculations within the model code. The sediment transport component of EFDC, as reported by Hamrick (1996), is somewhat simplistic. Standard excess-stress-type sediment mobilization and reworking terms are included in the model, the parameters for which must be supplied by the user (Hamrick, 1996). The model does not account for bed armoring which field studies (e.g., Amos *et al.* 1992) have shown to be an important process in many coastal situations. In addition, consolidation of sediments on the bed is not accounted for in EFDC. Recent applications of sediment transport models (e.g. Ziegler and Nisbet, 1994, Gailani *et al.* 1991) indicate that bed armoring and consolidation can be important processes in estuarine settings and therefore necessary to be represented in a sediment transport model. On the other hand, there are few models extant with this level of sophistication, many of the associated sedimentary processes are not well-formulated, and it is dubious that this capability would be needed in the TMDL determinations anticipated for Texas estuaries.

The heat budget terms are taken directly from the NOAA Geophysical Fluid Dynamics Laboratory's atmospheric heat exchange model (Rosati & Miyakoda, 1988). It appears that, unfortunately, these are based on the old concept of heat exchange being driven by the departure from an equilibrium temperature, and governed by a "heat-exchange coefficient." This approach has been completely abandoned in heat-budget work on lakes and estuaries, in favor of the much more accurate approach using explicit formulae for fluxes of radiation, conduction and latent-heat transfer.

EFDC also includes in principle options to model water quality. This is accomplished by "coupling" the hydrodynamic model to a separate "water-quality" model, coupling activated by the user by setting option switches in the input deck. It is not made clear in the model reports (Hamrick, 1992, 1996) exactly how this is accomplished within the computer code, and the resources of this project did not permit direct evaluation of the model operation. The author refers to "internal linkage processing procedures" but these are nowhere described. Hamrick (1996) indicates that the companion model is an "embedded" water quality model WQ3D, citing "Park, 1995," a reference omitted from the bibliography. The VIMS version of EFDC has a companion model named HEM-3D (Park et el., 1995), which we suspect is the same model.

HEM-3D is fundamentally the kinetics terms from CE-QUAL-ICM, developed for Chesapeake Bay (Cerco and Cole, 1994). The sediment process model emphasizes chemical and biological transformations in the bed sediments and the exchanges with the overlying water column, as developed by DiToro and Fitzpatrick (1993). There are two versions of HEM-3D, the "full version" that includes a complement of 48 separate state variables for the water column and sediment compartment, and the "simplified version" in which the state variables have been stripped down to 9 in the water phase and 23 in the sediment process compartment. Clearly, the adjective "simplified" is a relative term.

EFDC can also output transport fields for input to independent water quality models. The model presently has an option to be coupled with WASP5 and CE-QUAL-ICM (Hamrick, 1996), in that hydrodynamic output files can be generated already in the format for input into these water-quality models. Therefore in a TMDL project EFDC could be used as the hydrodynamic model and WASP5 could be used as the water quality model.

EFDC is perhaps the three-dimensional hydrodynamic code that is most closely associated with TMDL projects. The principal author of the model, John Hamrick, is presently employed at Tetra Tech, Inc., which is involved in several TMDL projects and developed BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) for the USEPA. A setting where EFDC was selected for a TMDL project involving three-dimensional modeling is South Puget Sound (Cusimano, 1999). In this case EFDC was chosen by the Washington State Department of Ecology because it is in the public domain and is broad in scope, including hydrodynamics, sediment transport and nutrient cycling.

Although EFDC is becoming associated with TMDL projects, it is not well established in the academic/research environment. Unlike virtually all of the recently developed and widely used three-dimensional hydrodynamic models (e.g. ECOMsi, TRIM, TRISULA-3D, SCRUM), the numerical methods and their coding in a solution algorithm of EFDC have not been published in peer-reviewed literature but instead in "gray" (not peer-reviewed) literature. More significantly, there is a rather sparse history of application of this model. Programming flaws, omissions in the development and analysis of a numerical method, and failures of process formulations are frequently disclosed as a model receives wide application by a variety of users and in a variety of applications, all of which is promoted by publication in the peer-review process. Our literature search has not uncovered any publications of applications using EFDC in peer-reviewed journals, but only in university reports and conference proceedings. In contrast, over one hundred applications of the Princeton Ocean Model can be found in leading peer-reviewed journals. In part, this is a liability that will be suffered by any new model just beginning to receive application. Because EFDC has not undergone a peer-review process, the numerical methods of EFDC are not established in the academic/research community of three-dimensional hydrodynamic modelers. Neither the sediment transport nor water quality capabilities of EFDC have a history of use in many projects, and similarly lack suitable testing. For this reason, there is a certain amount of risk entailed by adopting a new model such as EFDC since it cannot be expected to be as reliable as models that have been applied by a variety of users and repeatedly documented in peer-reviewed literature.

In conclusion, EFDC may be the best choice among the candidate models for some TMDL studies in estuaries and coastal regions, particularly if wetting and drying capabilities are required. However, the numerical method is not established in the academic/research community and many aspects of this model are not well tested. In addition, preparation of inputs and, particularly choice of model options, will require a great deal of time and expertise on the part of the user. Thus EFDC should be expected to be more difficult to use and less reliable than other candidate models. In Texas, its greatest potential utility is in the coastal estuarine setting.

EFDC is coded in FORTRAN77 for maximal transportability, and is a flexible code in the sense that it provides many options to the user. The source code is currently 52124 lines broken into 145 subroutines. Batch files for compilation are available (Hamrick, 1996). EFDC is expected to be much less computationally intensive than POM, because a more efficient numerical method is used, though little information is available on benchmarking and comparative resource demands. A typical range of grid points for simulation of estuaries is 50,000 to 500,000. Based on application of similar three-dimensional models (Gross et al., 1999) the run-time for 100,000 grid points is expected to be a minimum of 1 hour of CPU time per week simulated on a top-end PC platform. The code is freely available from VIMS for research and commercial use. VIMS charges a $ 200 administrative fee to offset the transmission costs and the (inevitable) special requests from prospective users (sending reports, answering e-mail questions, etc.). This fee is fully refundable if the user is dissatisfied with model. The user is asked to sign a Software Release Form beforehand, which articulates the policy of refundable administrative fee, and indemnifies VIMS from liability due to a new user's misapplication or from application of additional users that obtain the model from re-distribution of the code.

Model: **EPIC (Erosion/productivity impact calculator)**

Source: Agricultural Research Service
U.S. Dept. of Agriculture
Grassland, Soil & Water Research Laboratory
808 East Blackland Road
Temple, TX 76502

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds (farm-scale catchment)
vadose zone (upper soil horizons)

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

EPIC is one of the family of models developed by the U.S. Department of Agriculture, including CREAMS, GLEAMS, SWRRB, and SWAT (Renard, 1993; Williams and Arnold, 1993). EPIC is described as a "field-scale" model (up to 100 ha) and was designed to evaluate agricultural management strategies. Its principal advantage is the great detail of surface-flux and plant growth processes, including heat and energy budget at the surface, evapotranspiration, various cropping alternatives and drainage and tillage alternatives. The model even includes a stochastic "weather generator". These details allow computation of a range of field processes, including wind erosion, leaching of nutrients and pesticides, and infiltration to the groundwater.

A complete detailing of the mathematical expressions of the processes included in EPIC is given by Williams (1995). There is no geographic resolution to the model, that is, all of the inputs and processes are assumed to apply to the modeled "field" in a homogeneous manner. The model is considered to be continuous in time, i.e. its time discretization is primarily driven by the resolution of the inputs. Conceptually, it can be viewed as a detailed depiction of a soil/plant system at a single point in the landscape. It is therefore incapable of depicting the integrated effect of landscape variables on runoff. On the other hand, it simulates the detailed variation in time in various weather regimes, and can therefore be used to depict year-to-year variation in climate.

The main applications reported in the literature are evaluations of alternative agricultural management tactics. Holmberg et al. (1998) used EPIC and AGNPS to compute agricultural nitrate loads to Lake Decatur, Illinois and to evaluate various BMP options. McIntosh et al. (1993) addressed a similar problem of eutrophication in the southern Green Bay, Wisconsin area, due to agricultural nutrient and sediment loading, in which comparative simulations of sediment losses were determined using EPIC, SWRRB and AGNPS. EPIC was operated for different BMP strategies, and provided "edge-of-field" inputs to AGNPS and SWRRB. AGNPS was used to integrate the individual farms into small basin simulations with various integrated management strategies. Sugiharto et al. (1994) describe a similar exercise in applying AGNPS and EPIC to sediment and phosphorus loadings under twenty (count them, 20) different management strategies for dairy-farm dominated watershed.

Reyes and Cecil (1997) evaluated surface runoff volume predictions of GLEAMS, EPIC and WEPP; and the soil loss predictions of GLEAMS, RUSLE, EPIC and WEPP including comparison with observed data from experimental plots located near Greensboro, North Carolina, using conventional tillage, strip tillage, no till controlled traffic, and no till full traffic. They found that while EPIC and WEPP satisfactorily predicted runoff none of these models satisfactorily predicted soil loss. Yoon et al. (1997) similarly compared three models, GLEAMS, EPIC and WEPP, to a field-sized watershed in the Tennessee valley region of Alabama, with two tillage systems, three years of conventional tillage followed by three years of conservation tillage of cotton. They evaluated the model predictions of both runoff and losses of sediment, as well as losses of N and P, finding that GLEAMS and EPIC underpredicted NO_3 losses in runoff for both tillage systems. EPIC simulated tillage effects on soluble-P losses better than GLEAMS but poorly predicted annual organic-N and P losses in sediment, mainly due to overpredicted sediment losses. The GLEAMS prediction of annual organic-N and P losses in sediment was more acceptable than that of EPIC. WEPP apparently performed best of the three, with predicted sediment losses close to observed data for both tillage systems. Bingner et al. (1989) carried out a comparison of EPIC, CREAMS, ANSWERS, SWRRB and AGNPS using data from Mississippi research watersheds. EPIC was found to predict runoff as well as the other models, but to be the poorest in terms of predicted sediment yield.

EPIC is coded in FORTRAN and runs on a rather minimal PC platform, but requires about 11 M of space on the hard drive. EPIC and supporting documentation can be downloaded from the BRC homepage site at:

http://www.brc.tamus.edu/epic/

BRC is experimenting with an online user-friendly interface that enables the user to easily set up and make model runs with EPIC. The log-in and model execution occurs from the Internet site:

http://brcsun15.tamu.edu:8000/humus/cgi-bin/epic/epicintro.html

Model: **EUTROMOD**

Source: North American Lake Management Society
PO Box 5443
Madison, WI 53705-5443

1. Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

lakes and reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☐ yes	☑ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

[no information available]

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☐ yes	☐ no

(most recent application within the past five years)

(4) Model conceptual philosophy

Deterministic	☐ yes	☑ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

EUTROMOD is a relatively limited model, designed for application to watershed-derived nutrient loading in lakes. The model is a spreadsheet program that employs gross statistical relations (e.g., USLE) to determine phosphorus and nitrogen loadings to a model lake, treated as a continuously stirred tank reactor. The lake response is derived from regional data bases from the National Eutrophication Study and statistical models fitting that data. Apparently, the model is limited by the data used in its development to small reservoirs in the Southeast. However, EUTROMOD is reported to be one of the models being used by the State of Kansas for its TMDL determinations.

Little recent information is available in the literature on applications of EUTROMOD. The only reference turned up in the present survey is the project of Hession et al. (1996a,b) who used EUTROMOD to evaluate risk probabilities of phosphorus impacts on Wister Lake in Oklahoma, which is impacted by agricultural loadings. EUTROMOD simulations were embedded in a Monte Carlo procedure to determine probability distributions of annual phosphorus loads to the lake due to natural variability in hydroclimatology and to uncertainty in parameter estimation.

The model with documentation is available on 3.5 or 5.25 (!) diskettes from the above address for $ 80. No information could be found on the details of model operation, but presumably it is designed to operate with early versions of LOTUS 123 or EXCEL.

Model: **EXAMS (Exposure Analysis Modeling System)**

Source: Environmental Protection Agency
Center for Exposure Assessment Modeling
960 College Station Road
Athens, GA 30605-2700

(1) Stated physical system(s) for which model is applicable.

Reservoirs and lakes

Representative of Texas hydrological systems and Texas hydroclimates:

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☐ yes	☑ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

[but see discussion]

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

[but see discussion]

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

Many of the trace chemicals of concern in potential human impacts involve complex kinetics, for which existing models are inadequate. EXAMS is a model developed by EPA to specify and store the properties of organic chemicals and ecosystems so that a user may conduct evaluations of the probable aquatic fate of these chemicals (Burns, 1997). It is intended to combine the loadings, transport, and transformations of a chemical into a mass-balance-based computational accounting. EXAMS includes process models of the physical, chemical, and biological phenomena governing the transport and fate of compounds. Use of EXAMS is intended to facilitate complex models of kinetics, e.g. correlation of molecular spectroscopic properties with chemical and microbially mediated hydrolysis rates; and a combination of linear free energy theory, structure-activity relationships, and perturbed molecular orbital methods (Donaldson, 1992). The current version EXAMS-II strictly applies to surface waters. The EPA Office of Pesticide Programs (OPP) employs a modeling system composed of SWRRB and PRZM models for runoff and EXAMS II for fate and transport in surface waters (Zubkoff, 1992).

It must be emphasized that EXAMS-II is a different sort of model than those considered in this report. The object of the model is to compute the "expected environmental concentration" (EEC) of a chemical or biochemical parameter. This is conceived to be a generalized concentration complex of the original compound and various kinetic products ("daughters") in a sort of quasi-equilibrium, spread through the receiving watercourse and elements of the ecosystem. It is not intended to be specific to a particular waterbody or site within that waterbody. According to Burns (1997), "the goal, at least in principle, is to predict EECs for a wide range of ecosystems under a variety of geographic, morphometric, and ecological conditions."

The model includes an integrated database display of chemical parameters, which the user can invoke interactively to refine the kinetic model of a particular compound. For example, the partition coefficients of the compound on sediment phases can be estimated as a function of the organic carbon content of the sediments based upon the compound's octanol-water partition coefficient, which is included in the data base. EXAMS is described as a deterministic, rather than a stochastic, model "...in the sense that a given set of inputs will always produce the same output" (Burns, 1997). This definition implicitly equates a non-deterministic model with one that has a built-in random process, hence yields different responses every time the model executes, even though the inputs may be unchanged. We note that in the present study, this definition is not sufficient to categorize the model as "deterministic" since the said output may arise from a statistical regression equation, which will always be the same for a given set of inputs.

Basically, the user must supply information on process kinetics, ecosystem structure and hydrodynamic transport (which may be derived from a separate model) to EXAMS, which then combines this information to produce a kinetic "map" of the compound in question in each of the system compartments. Transports in the model are computed by a finite-difference solution to a mass-budget equation on a 3-dimensional system of rectangular elements, but the "hydrological pathway" and advective currents are user-supplied, as are the mixing coefficients. The strongest utility of the model is in situations in which kinetics dominates the receiving water concentrations of an introduced substance or in which a general estimate of "residual" concentration is needed to assess the relative threat of toxicity. It is not considered to be of immediate utility in most TMDL determinations for Texas, the possible exception being a TMDL determination of a highly toxic, highly reactive constituent. The most appropriate physical system for application of EXAMS would be an analog to a continuously stirred tank reactor (CSTR), such as a small reservoir.

Relatively few applications are reported in the literature. An early application by Henry and Burns (1990) carried out a sensitivity analysis of parameters used in EXAMS (Version 2.92), based on tidal and nontidal models using actual data on seasonal variation in flow and temperature in the Delaware River. The chemicals examined were vinyl chloride, hexachlorobutadiene and benzo(a)pyrene. High and low values for river flow and temperature were run in the tidal and nontidal models resulting in eight "versions" of the model. More than a 300-fold decrease was found in the upstream water-column concentrations resulting from a 7-fold increase in flow in the tidal models. For all other cases, the changes in water column concentrations between model runs were either proportional to the changes in the value, or minimal (< 50%). There were significant differences in the concentrations in the benthic and suspended sediment and the relative distribution of the mass of the chemicals between the water column and the benthic sediment due to differences in chemical properties.

Cousins et al. (1995) report field validation of EXAMS II carried out on a stretch of a UK lowland river, the River Calder in West Yorkshire, where there is a point source of aniline and lindane, from a sewage treatment plant discharge. Aniline and lindane were measured in river water samples, TSS and sediments and in samples from the STP effluent. Good agreements were reported between the model predictions and the measured values for the water and bed sediment, but the levels measured in the suspended particulates were significantly higher than those predicted, apparently due to the inappropriateness of the equilibrium partitioning approach employed by EXAMS.

Siewicki (1997) evaluated fluoranthene impacts from urban runoff in a portion of Murrells Inlet, South Carolina. Kinetic rate constants for sediment-associated fluoranthene and fluoranthene runoff concentrations from earlier studies were used. EXAMS II was used to simultaneously integrate environmental conditions and loading in the estuary with the physico-chemical characteristics of fluoranthene. Factors predicted to affect oyster exposure were non-point source runoff loading and base (background) loading, with some effect from non-point source hydrologic flows.

Information and the model code can be downloaded from the CEAM Internet site:

ftp://ftp.epa.gov/epa_ceam/wwwhtml/softwdos.htm

The model is described in a user's manual (Burns, 1997) available from this site. Although the FORTRAN source code can be made available to the user (by a separate written request to CEAM), the user's information strongly recommends against any modification of the code, stating that this "...should be attempted only by experienced research personnel with substantial expertise in FORTRAN development tools and the EXAMS modeling system."

Model: **GLEAMS (Groundwater Loading of Agricultural Management Systems)**

Source: Agricultural Research Service
U.S. Dept. of Agriculture
Grassland, Soil & Water Research Laboratory
808 East Blackland Road
Temple, TX 76502

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds (farm-scale catchment)
upper soil horizons

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Because GLEAMS is similar to CREAMS, its level-2 and higher evaluations are included in the review of that model.

Discussion

GLEAMS was adapted by the Agricultural Research Service of USDA from CREAMS, extending this model to include vertical flux of soluble tracers into the subsurface, with much greater detail in the soil percolation process. The near surface soil profile is depicted by a series of computational layers, tied to the soil horizons. This allowed more sophisticated modeling of root zone processes, effects of irrigation and tillage, and flux of constituents, especially pesticides. Details of the hydrology of the model are given by Knisel and Williams (1995). The geometry of the model could be said to be one-dimensional—vertical variation through the root zone only—because, like CREAMS, GLEAMS treats a small, spatially homogeneous area, from which runoff and waterborne-parameters are determined.

Morari and Knisel (1997) report a modification to GLEAMS version 2.10 to represent water and solute movement in cracking clay soil. Because there is much commonality in the hydrology components of the model, hydrological and surface-loading validation for CREAMS is generally considered to also validate GLEAMS. While GLEAMS does not include the vadose zone *per se*, it was designed with the intent to be coupled to an appropriate vadose zone model.

One of the main purposes for the development of GLEAMS was to better simulate the leaching and efflux of pesticides from agricultural operations (Knisel and Williams, 1995; Cohen, 1996). Craig and Weiss (1993) used GLEAMS to simulate pesticides entering surface water from USDA Forest Service nurseries and subsequent risks from human oral exposure to the stream water. Several pathways of contamination exist, and GLEAMS was used to determine their relative magnitudes. Goss (1992) used GLEAMS to evaluate various categories and combinations of pesticide loss, based upon 40 thousand runs of the model. The model input data varied soils and pesticides properties, and the model-simulated pesticide losses were categorized into leaching, sorption on sediment in runoff, and solution in runoff. Kaluli et al. (1997) compared model prediction to measurements of atrazine in the top 20 cm (root zone) of a clay loam corn field in southwestern Quebec. Three models were tried, PRZM, GLEAMS, and PESTFADE. PRZM was found to perform better than the other two models. When the kinetics of PESTFADE were improved with macrospore flow and better sorption kinetics, it performed better. While this illustrates the importance of the modeling of these processes, it is not clear how the kinetics differ among the models and whether the discrepancy would be eliminated if the same kinetics were used.

Leonard et al. (1992) applied GLEAMS to evaluate potential pesticide runoff of two similar pesticides from one soil, for the purpose of comparing annual means and single events. They emphasize the importance of the hydrometeorology for a model application, noting that "care must be exercised in selecting representative climatic periods." For short half-life pesticides, initial rainfall events on or near the day of application will often contribute most to annual pesticide lost, in which case an "event" simulation may be preferable to a long-term average. They also concluded that with annual totals of simulated pesticide runoff, long-term 50-yr simulations are preferable to short 10-yr simulations. Neary et al. (1993) report on ten years of watershed-scale research on pesticides in forested watersheds throughout the southern U.S. They used data on various forestry pesticides to verify GLEAMS, CREAMS, and PRZM models. Shirmohammadi and Knisel (1994) validated GLEAMS against leaching data from lysimeter experiments conducted in Mellby soil near Uppsala, Sweden. They conclude that the GLEAMS model performed "in a reasonable manner." Shirmohammadi et al. (1998) reported extended work on nutrient losses through tile drainage with similar results.

Zacharias and Heatwole (1994) evaluated the pesticide-prediction performance of GLEAMS and PRZM using field data from a plot under no-till corn in the Coastal Plain region of Virginia. Differences in hydrology simulations were traced to the different formulations of evapotranspiration. Runoff and soil moisture were found to be predicted reasonably well "after adjusting important hydrology parameters." They concluded that overall GLEAMS represented pesticide behavior in soil better than PRZM. They also found that model predictions of pesticide fate and transport are not sensitive to curve number or field capacity of the soil.

Diebel et al. (1992) used GLEAMS and CREAMS in concert with an economic model to evaluate alternative policy scenarios, including cost sharing for green manures, restrictions on atrazine application levels, chemical taxation, restriction on potential chemical and nitrogen levels in surface and groundwater, and land-retirement programs. Yoon et al. (1994) applied GLEAMS to predict nutrient (N and P) losses in surface and subsurface runoff, and their concentrations in soil layers, following application of two rates (9 and 18 t/ha) of poultry litter and a recommended rate of a commercial fertilizer on conventionally tilled corn plots at the Tennessee Valley Substation in Alabama. The GLEAMS simulation was compared to field data and it was found that both soluble and sorbed P losses in surface runoff and NO3-N in leachate and soil layers "were not consistent with field data." The predicted N losses were too high, and the predicted P concentrations in leachate were too low.

Minkara et al. (1995) present an application of GLEAMS to evaluate nitrate leaching below the root zone due to poultry litter application to pine seedlings. A field experiment was carried out with six treatments: 4.5, 9.0, and 18.0 t/ha of poultry litter, 4.5 t/ha of poultry litter with intensive weed control, commercial fertilizer, and a control. For all treatments, they found NO_3-N concentrations in soil leachate to far exceed 10 mg/L during the first seven months then dropping below 10 mg/L for the rest of the 15-month study period. GLEAMS was reported to accurately predict NO_3/-N leachate-concentrations for the poultry litter treatments, but to underestimate concentrations for the control and commercial fertilizer treatment. Also, GLEAMS-predicted soil NO_3-N concentrations were higher than average measured values in most cases.

Reyes and Cecil (1997) evaluated surface runoff volume predictions of GLEAMS, EPIC and WEPP; and the soil loss predictions of GLEAMS, RUSLE, EPIC and WEPP including comparison with observed data from experimental plots located near Greensboro, North Carolina, using conventional tillage, strip tillage, no till controlled traffic, and no till full traffic. They found that while EPIC and WEPP satisfactorily predicted runoff none of these models satisfactorily predicted soil loss. Yoon et al. (1997) similarly compared three models, GLEAMS, EPIC and WEPP, to a field-sized watershed in the Tennessee valley region of Alabama, with two tillage systems, three years of conventional tillage followed by three years of conservation tillage of cotton. Model comparisons considered both runoff and losses of sediment, as well as losses of N and P. They found that GLEAMS and EPIC underpredicted NO_3 losses in runoff for both tillage systems. EPIC simulated tillage effects on soluble-P losses better than GLEAMS but poorly predicted annual organic-N and P losses in sediment, mainly due to overpredicted sediment losses. The GLEAMS prediction of annual organic-N and P losses in sediment was more acceptable than that of EPIC. WEPP apparently performed best of the three, with predicted sediment losses close to observed data for both tillage systems. Persicani (1996) did a comparative evaluation of the sensitivity of four models, MOUSE, GLEAMS, TETRANS, and HYDRUS. GLEAMS was found to be moderately sensitive to hydraulic conductivity and potential evapotranspiration, highly sensitive to the input parameters related to runoff, sorption, and degradation submodels, as well as soil water content at field capacity. Some limited and inconclusive comparisons between measured and simulated alachlor leaching were also reported.

An example of the use of GLEAMS for subsurface water modeling is the report of Desmond et al. (1996) who adapted GLEAMS for prediction of daily water table elevations, testing performance against field data from Aurora, NC. A similar application was made by Reyes et al. (1993) who report an improvement to the hydrological components of GLEAMS to account for shallow water table fluctuations, in replacing the evapotranspiration and percolation with algorithms appropriate to a shallow water table, and adding routines to account for depression storage, and upward flux from the water table. In a comparison with seven years of measured data from a runoff-erosion-drainage experimental plot at Baton Rouge, Louisiana, the improved model predicted surface runoff volume essentially dead-on the observed runoff volume, while the original GLEAMS underpredicted by 54%.

GLEAMS can be downloaded from the USDA Internet site at:

http://arsserv0.brc.tamus.edu/nrsu/glmsfact.htm

Probably the greatest potential value of GLEAMS in the Texas TMDL process would be for specialized study of pollutants applied to a surface subject to weathering and runoff, e.g. chicken-litter disposal. Such an application would be in conjunction with larger scale models addressing the watershed.

Model: **GWLF (Generalized Watershed Loading Functions)**

Source: unknown

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	➢ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ➢ yes ❑ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

GWLF proved to be a very simplified watershed-type model, in fact a series of statistical models of runoff-borne constituents, which has extremely limited application. The original model formulation and application is due to Haith and Shoemaker (1987), and was adapted by Howarth et al. (1991) for application to the Hudson River watershed. Swaney et al. (1996) extended this work by incorporating GWLF into a GIS shell and improving the detail of input data on weather. The model was used for estimating annual loads of sediment and organic carbon to the Hudson River from various land uses in the upper portion of the basin. With these modifications, the estimated loads increased 10% for sediment and 20% for total organic carbon. The model was used to estimate runoff loads of sediment and TOC for past historical scenarios of development of the Hudson basin.

Model: **HSPF (Hydrological Simulation Program – FORTRAN)**

Source: Environmental Protection Agency
Center for Exposure Assessment Modeling
960 College Station Road
Athens, GA 30605-2700

Also: U.S. Geological Survey
Hydrologic Analysis Software Support Program
437 National Center
Reston, VA 20192

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
streams and rivers
lakes and reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☑ yes	☐ no
substantially altered hydrology due to urbanization	☑ yes	☐ no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☑ yes	☐ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no

relatively shallow lakes ☑ yes ☐ no

seasonal temperatures fall below that of maximum density ☑ yes ☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution ☑ yes ☐ no

in public domain ☑ yes ☐ no

flexible in its licensing requirements ☑ yes ☐ no

capable of transporting to variety of PC platforms ☑ yes ☐ no

source code available to potential users ☑ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria (watershed models)

(1) Model formulation

differentiation of soil types, vegetation, land-use? ☑ yes ☐ no

satisfactory determination of runoff? ☑ yes ☐ no

satisfactory disposition of surface flow? ☑ yes ☐ no sediment mobilization & transport included? ☑ yes ☐ no

temporal integration: ☑ event only ☐ continuous

receiving water: ☑ included in model ☐ external link ☐ none

inclusion of features extraneous to Texas? ☑ yes ☐ no

(2) Numerical solution

method for numerical specification of terrain and drainage network:
☑ manual input ☐ import of standard files ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

minimum hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Screening Level 2 Criteria for stream/river models

(1) Model formulation

variable channel geometry? ☐ yes ☑ no

variable bed characteristics? ☐ yes ☑ no

time integration: ☐ steady-state only ☑ time varying

accommodates flood-type hydrograph? ☑ yes ☐ no

basis for current computation: ☑ direct input ☑ continuity only
☐ kinematic wave ☐ complete hydraulic model ☐ other

water quality (mass transport) capability included? ☑ yes ☐ no

sediment dynamics in stream included? ☑ yes ☐ no

peripheral sediment loads included?	☑ yes	☐ no
capability to include channel estuaries?	☐ yes	☑ no
run-of-river reservoirs?	☑ yes	☐ no

Level-2 Screening: ☐ **eliminate** ☑ **consider**

Discussion

HSPF is described (Donigian et al, 1996) as a "comprehensive package for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants" and as the “only comprehensive model” that allows the integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical interactions" (Donigian and Huber, 1991). “Among the best choices” for full-scale simulation models for urban areas, “SWMM and HSPF are clearly the most versatile and most widely applicable of the models” according to the review of Donigian and Huber (1991). Of the models reviewed here, HSPF formally presents probably the most capabilities for addressing a range of problems in surface water resource management.

HSPF is based upon the concepts of the mechanistic Stanford Watershed Model, and originally incorporated aspects of the early watershed models ARM (Agricultural Runoff Management) and NPS (Nonpoint Source) (Donigian et al., 1995). There are three "application modules" in HSPF that address types of watercourses: PERLND and IMPLND are watershed loading models treating, respectively, pervious and impervious catchments, and RCHRES is a one-dimensional (section-mean) stream model that functions as the receiving watercourse. The model is fully dynamic, and includes provision for continuous modeling of runoff and sediment mobilization with an array of both generic water-quality parameters, and specific coupled kinetics, including BOD-DO, P- and N-nutrients and phytoplankton interactions in the watercourse, and pesticides. Over the years, many additions and expansions of the model have been made. For example, an array of options is available for depicting various agricultural land treatments. One-dimensional lakes can be incorporated into the stream segmentation. The subsurface budget is modeled as a two-layer system, which can interact with the surface resource through plant function and interflow, and provision for percolation to a deep aquifer is included. (The aquifer itself is not modeled, but is treated as a sink of water.)

Segmentation of the receiving water system (which can include a conflowing network of tributaries) is linked closely to the segmentation of the watershed. Overall subdivision of the watershed into computational catchments is based upon distribution of meteorological stations and soil types, which are considered to define segment "groups", each of which is assumed homogeneous in climatology and soils. Each such group is further subdivided according to "land use" classifications, which can include vegetation assemblages, agricultural cropping patters and urbanization. The boundaries of these watershed segments then define reaches of the receiving watercourse. Any further refinement of the receiving stream (to represent for example breaks in channel slope, presence of dams or fall lines, or confluence of tributaries) may entail further subdivision, and an associated subdivision of the drainage area for each of the resulting channel reaches. Because the complexity of the input file structure increases geometrically with the number of such segments, the user is advised to be parsimonious in their specification.

The most important subroutines ("compartments") of PERLND for the determination of watershed loadings in Texas environments are PWATER, basically the Stanford Watershed Model surface water budget, SEDMNT and PQUAL. There is also a collection of compartments that together treat sediment and water-quality aspects of agricultural activities. PWATER includes surface storage, infiltration flux and storage through two soil zones and two groundwater layers, one of which is active in the simulation and drives baseflow in the receiving stream, and one of which represents the deep percolation sink of water. There is also a separate storage accounting attributed to interflow to downslope segments or the receiving stream.

HSPF can model receiving water components as completely-mixed (laterally and longitudinally) segments, using a sub-module in the HSPF model. The “reach-reservoir” sub-module can be used to establish long-term averages of water quality constituents, although simulation in a more complex model would most often be preferable. The sub-module can also be used in the calibration and verification process by comparing simulated values versus data on the “order-of magnitude” scale.

The design philosophy of HSPF was to make the model operate as several modules in series, which will allow the passing of output from any one module as input to another in the series. Another purpose of this modular design was to allow HSPF to be readily coupled to water quality models. HSPF has been applied to establish loads of solids and other water quality constituents as inputs to in-stream models, such as EFDC. The total load from HSPF includes the contribution from the groundwater and overland flow.

The mechanisms employed for the key processes, such as sediment detachment, overland flow, and surface erosion, are given limited description in the model documentation, and must be dug out of the user's manual or the code algorithms. The impervious land segment module does not seem to differentiate soil types. Moreover, the basis for the algorithms is poorly stated. Most of the sources for the model are "gray" literature. For example, the sediment detachment and transport model references a Stanford Technical Report from the 1960's (Negev, 1967) with surface practice modeling "influenced" by the Universal Soil Loss Equation (USLE). The input manual indicates that the HSPF model differentiates soil types in pervious land segments as either inorganic or organic. How these two types are treated differently is unclear. The equations for soil production and removal contain a parameter for management practice factor based on the “P” factor of the USLE, which was introduced in order to better evaluate agricultural conservation practices. Soil detachment equations contain a parameter that is the fraction of the land covered “by snow and other cover.” The area covered by the snowpack is calculated in the model based on air temperature, dewpoint, etc. “Other cover” is a parameter that will typically be the fraction of the area covered by vegetation and mulch.

While literally every process that is identified in the surface water budget corresponds to an equation in HSPF, It is difficult to judge the relation of these equations to the standard models for those processes as treated in the literature. Many of the discussions in the user's manual are based upon qualitative sketches of how a process "ought to work" followed by mathematical equations represented the curves in the sketches. Although this is certainly one means of developing a process model, the separate relations must be tested against measurements.

In some urbanized areas, IMPLND may be important. This treats the surface water budgets of impervious watersheds, and is stated (Donigian et al., 1995) to include most of the accumulation and wash-off functions of SWMM and related urban runoff models. This includes the capability to remove solids by processes other than storm runoff, so that street sweeping, decay and wind deflation can be addressed. Again, the model consists largely of arbitrary functions that behave in an "expected" way, governed by empirical parameters, which the user must supply as part of the input file.

The direct incorporation of a receiving water component RCHRES in HSPF offers the convenience of directly linking the watershed outputs into the stream response in a seamless way. Few watershed-loading models have this capability, and it can be debated whether it is preferable to having a completely external receiving watercourse model for which the user must manipulate output files to drive the receiving model. The RCHRES includes compartments (i.e., subroutines) for the usual water-quality concerns, e.g. BOD-DO, nutrients and phytoplankton, sediment transport, and general water-quality constituents with formally specified source/sink terms. The hydraulic compartment, which determines the advection terms in all of the others, is based upon a time-interval budget of water volume between inflow from the above reach, user-specified outflows, and discharge to the next downstream reach. The hydraulics by which the last is computed is a user-defined relation between Q and depth (and the associated parameters reach volume and surface area, which are functions of water depth based upon cross sections of the stream). The model does not carry out this hydraulic computation, but must have the functional rule as an input for each segment reach.

The subroutine SEDTRN computes sediment transport in the stream channel. HSPF uses three sediment types: clays, silts, and sands. Suspended and bedload transports are budgeted separately. Settling and resuspension differentiates cohesive (clays and silts) and non-cohesive (sand) solids. The three categories are assumed independent of the other (so that, e.g., armoring is not addressed). The user must partition the watershed runoff load into the three grain-size categories. The user selects among three choices of relations for modeling deposition and scour, which are extracted from an earlier modeling project at Batelle (Onishi and Wise, 1979). Again, this is an example of HSPF relying upon a "gray" literature result as its primary source. (The reader should note that this particular report is labeled "draft", 20 years after its completion.) The method for noncohesive sediments is based upon critical-stress formulations of scour. Accumulation or scour of bed sediments is totaled through the simulation to predict net streambed changes.

Up to ten waterborne constituents can be modeled in a single simulation. The constituents can travel via overland flow, interflow, or groundwater flow. The user specifies which mechanisms are considered for each chemical. The interflow and groundwater transports are simple loading relationships; the user specifies the chemical concentration in each area and the flux is that concentration multiplied by the calculated flow. Chemical processes modeled include hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption. Constituents can be transported by overland flow in different phases: dissolved or entrained in the water, or sorbed to the solids in the water column. The association of constituents to solids is based on simple relationships with sediment and water yield. The constituents can be proportional to sediment removal based on user-inputted “potency factors,” which indicate the constituent’s strength relative to the sediment removed from the surface. Atmospheric deposition and other external loading of constituents can also be specified by the user. These generalized relationships allow the user to simulate any constituent in a simplified manner, using basic user-specified parameters. The user inputs the partition coefficients and the kinetic rates for adsorption for each parameter involved.

In addition, HSPF has specialized transport routines the transport of agricultural chemicals (pesticides, nitrogen, and phosphorus). These routines simulate detailed nutrient and pesticide processes. These routines require detailed chemical data for all chemicals modeled. If detailed data are not available, it is suggested that the user use the simplified relationships described in the above paragraph.

Operation of the model is complicated, but exemplifies the problem of coding a general model for time-varying simulation. Such a simulation necessitates long time series of all of the input data streams, which will be defined for all watershed segments or (in the case of meteorology) segment groups, and for many (perhaps all) stream segments. Acquisition, re-formatting and management of these input time series files represent much of the effort of application of the model. Manipulation of input and output time-series files is controlled by a series of modules (more, in fact, than the number of *computational* modules), and the large array of options leads to a complex input-file structure. The operating module of HSPF constantly updates the state variable time series based on the user-specified time scale. This allows the user to dictate the time scale of all state variables, allowing the user the flexibility for integrating over the proper time period for any given simulation.; i.e., a flood period could be updated on a scale of hours, whereas a longer simulation can be updated on a daily basis.

Extensive data are needed to run the model. Topography data in the form of a digital elevation model, or from 1:24,000 scale digital terrain maps, are preferable for defining the distribution of slopes in the watershed, and to define the boundaries of the watershed and subwatersheds. Complete rainfall records are necessary, and data on evaporation and evapotranspiration, temperature, and solar intensity are desirable for many of the options. Default values are available for many model parameters, although their use solely to facilitate model set-up is ill-advised. Depending upon user options, output from HSPF can include time histories of sediment loads, runoff rates, and nutrient and chemical concentrations. A summary of data requirements for typical HSPF applications that are specified in the user's manual (Bicknell et al., 1996, 1997) follows:

1. Precipitation and meteorological data (for simulation period)
    a. Hourly precipitation
    b. Daily pan evaporation
    c. Daily maximum and minimum air temperature
    d. Total daily wind movement
    e. Total daily solar radiation
    f. Daily dewpoint temperature

g. Average daily cloud cover

2. Watershed land use/land cover characteristics
    a. Topographic map/data of watershed and subwatersheds
    b. Land use/cropping delineation and acreages
    c. Soils delineation and characteristics

3. Hydrography and channel characterization
    a. Channel lengths and slopes
    b. Channel cross-sections and geometry
    c. Channel bed composition (e.g. particle distribution, nutrients, pesticides)
    d. Diversions, point sources, channelization segments, etc.
    e. Tributary area (and land use distribution) for each channel reach

4. Monitoring program observations
    a. Flow rates during all monitored storm events
    b. Flow volume/rate totals for storm/daily, monthly, annual
    c. Sediment concentrations and mass losses in runoff
    d. Chemical concentrations and mass losses in runoff
    e. Soil concentrations of chemical/nutrient forms, if available
    f. Estimated/actual chemical concentrations in precipitation
    g. Particle size distributions (sand, silt, clay fractions) of soils and eroded sediments

5. Other useful information
    a. Description/quantification of any other contaminant sources (e.g. point sources, feedlots) or other relevant information (e.g. ponds, dams, marshes)
    b. Technical reports or articles that analyze and/or summarize the monitoring data
    c. Soils characterization information for estimating model parameters

USGS has developed several interactive software shells to facilitate set-up and calibration of watershed models, which are particularly attractive for use with HSPF. One of these, WDM

(Watershed Data Management), has replaced the older Time Series Store module (Donigian et al., 1984). In order to assist in the data management process, an software application called ANNIE has been designed to help users interactively store, retrieve, list, plot, check, and update spatial- and time-series data for hydrologic models. ANNIE is a fully function data management tool which is completely compatible with HSPF. ANNIE uses a direct access file called the Watershed Data Management (WDM) file, which is currently used by both USGS and the USEPA for many hydrologic models and analyses. HSPF forms the basis (in a reduced version) for the watershed-loading model NPSM incorporated into BASINS.

HSPF has been applied to a variety of sites and a range of applications across the United States and internationally, representing a wide variety of hydrologic and water quality studies for long-term studies and over storm events (Barnwell and Johanson, 1981; Barnwell and Kittle, 1984; Lorber and Mulkey, 1981; Mulkey et al., 1986; Schnoor et al., 1987; Donigan et al. 1983; Donigan et al., 1990). About 50 applications are outlined by Donigan et al. (1995). Additional examples have included the LeSueur Basin in Southern Minnesota and the Upper Grande Watershed in Oregon (Donigan, et al., 1996 and Chen, et al., 1996). USGS Truckee-Carson Program, begun in 1990 used HSPF to simulate storage, flow, and water quality in a seven dam run-of-the-river-reservoir system. For this project, capabilities were added to the HSPF framework to include agricultural, municipal, and hydropower demands. Chen et al. (1998) adapted HSPF to predict water temperature variations as affected by shading and insolation variation in a forested watershed.

Cheung and Jivajirajah (1994) report an application to the Cattai Creek catchment, a largely rural watershed in Australia. Calibrations for eight water quality variables were carried out, and the model adapted to simulate a complex algal community. Rathman and Salbe (1995) applied HSPF to the Hawkesbury-Nepean river system in region of Sydney, Australia. In their judgment, HSPF "is the only model available that incorporates the wide range of significant processes involved." The modeling focused on the South Creek catchment, an urbanized watershed with both diffuse and point sources of nutrients. The model was used to project stream nutrients under various treatment scenarios. It is not clear whether any model validation work was carried out. Laroche et al. (1996) tested HSPF for predicting atrazine transport versus data from a 78 ha watershed in Quebec. Model parameters related to hydrologic and pesticide transport processes were calibrated. Only streamflows were verified, due to data limitations, the correlations between observed and simulated streamflows being 0.73, 0.87, and 0.90 for daily, weekly, and monthly intervals, respectively; for the calibration period, and 0.67, 0.91, and 0.93 for the verification.

Codner (1991) carried out a comparative review of SWMM and HSPF, in terms of "model structure, technical content, problem applicability, data requirements, and user friendliness". HSPF was found to be complex and difficult to use. While SWMM is reasonably "user friendly," its major problem was considered to be the difficult calibration due to the number of degrees of freedom in the model. Fontaine and Jacomino (1997) report a sensitivity analysis of HSPF for contaminated sediment transport, which of course depend upon predicted streamflow and the flux of sediment. This included use of an "extensive" database from a 6.2 mi^2 catchment in eastern Tennessee to first calibrate the model. They found the fluxes of sediment to be more sensitive than streamflow to changes in parameters for both flood and normal flow conditions, and the relative significance to vary according to the type of flow condition and the location in the catchment. Jacomino and Fields (1997) applied HSPF to a 16 km^2 catchment, comparing flows on an annual and monthly basis during a total calibration period of four years.

Smith et al. (1992) used HSPF in a GIS shell to develop a synthetic watershed sediment routing model, based upon relating sediment routing to the streamflow component of the model. They report an application to the 56.3 mi^2 North Reelfoot Creek watershed, in northwest Tennessee. Tsihrintzis et al. (1994, 1995) applied HSPF in a GIS shell (using ARC/INFO) to evaluate the impact of agricultural activities, specifically transport of sediments, nutrients, and pesticides, on streams and groundwater in South Florida. Input/Output for HSPF has been linked to the GIS program ARC/INFO (Al-Abed and Whiteley, 1995).

Desired capabilities that favor use of HSPF include the requirements to:

- Simulate periods of storm runoff and low flows
- Simulate a variety of timesteps, including hourly or daily

- Simulate the hydraulics of complex natural and man-made drainage networks
- Simulate results for many locations along a reservoir or tributary
- Compute a detailed water budget for inflows and diversions

The complexity of HSPF means that the user is required to have a high level of knowledge of watershed processes because input values are the driving force behind the model simulation. Improper parameterization of the input variables will cause the model results to have no value. The user has control of a wide array of input parameters, many of which can be spatially and temporally varied. The modular design of HSPF is meant to allow the user to customize application for certain processes by adding or substituting a user-coded module to the series. By observing standard coding practice, experienced users can implement additional customization through model modification, in terms of model improvements or "hard-wiring" for a specific application. Again, coding changes and data management must be done by an experienced modeler in order to properly get the full functionality of this model. It has been reported by the USEPA that "Although data requirements are extensive and running costs are significant, HSPF is thought to be the most accurate and appropriate management tool presently available for the continuous simulation of hydrology and water quality in watersheds."(Bicknell et al., 1996). However, it should be noted that a majority of the literature published on HSPF was written by modelers involved with its development. Therefore, care should be taken in interpreting comments concerning the model's overall acceptance and applicability to other environments.

HSPF is coded in standard FORTRAN-77 and can be used on many computer platforms. The model is available free of charge from the Center for Exposure Assessment Modeling, USEPA, and can be downloaded from the Internet at URL:

ftp://ftp.epa.gov/epa_ceam/wwwhtml/hspf.htm

or from the U.S. Geological Survey at:

http://water.usgs.gov/software/hspf.html

Model: **IDOR^{2D}**

Source: Water Resources Environmental Information Systems Laboratory
McMaster University
Hamilton, Ontario
Canada

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

lakes and reservoirs
estuaries

Representative of Texas hydrological systems and Texas hydroclimates:

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☑ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	➢ no

(3) Model program lineage.

Sufficient history of application ❑ yes ➢ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ➢ yes ❑ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ➢ yes ❑ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

IDOR2D is a two-dimensional vertically integrated hydrodynamic and transport model developed for coastal watercourses and lakes. It is marketed by McMaster University as a PC-based program coupled with ArcView, with a "user-friendly" GIS-based interface. It has appeared fairly recently (the first ever Annual Workshop on the model is scheduled for July 1999), and it appears that the only applications reported in the literature are by the creators of the model, e.g. Boyle and Tsanis (1998), Boyle et al. (1998), Tsanis (1998), Tsanis and Boyle (1998), Tsanis et al. (1994, 1996, 1998). A companion program IDOR3D has been applied to Lake Biwa in Japan, North Crete in Greece, Hamilton Harbour, Cootes Paradise, Lake Ontario and the Metropolitan Toronto Waterfront. There does not appear to be a GIS interface, and the information on the web page

http://water.eng.mcmaster.ca/pages/hydro.htm

suggests that its marketing has only begun.

Model: **IIHR Distributed Parameter Watershed Model**

Source: Iowa Institute of Hydraulic Research
The University of Iowa
404 Hydraulics Laboratory
Iowa City, Iowa 52242-1585

Information inadequate to complete Level-1 screening.

Discussion

The only literature source that could be located regarding this model is Jain et al. (1982). Considering the age of this publication, and the fact that there is no link to such a software product on the IIHR homepage given below suggest that a modern PC version of this model was never developed.

The model described by Jain et al. (1982) is a finite-difference solution to the equations of transport and momentum for overland and channel flow. Runoff is computed from the SCS Curve Number method, and sediment loading from the USLE. The model is coded in a rather primitive batch-run FORTRAN.

One other IIHR model was evaluated in this review, *viz*. CHARIMA.

The Internet homepage of IIHR is the following UR:

http://www.iihr.uiowa.edu/index.html

and includes sofware products and reports of the Institute.

Model:	**MIKE-SHE (Système Hydrologique Européen)**
Source:	Danish Hydraulic Institute Agern Allé 5 DK-2970 Hørsholm Denmark

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
streams and rivers
aquifers
vadose zone

(It is not clear whether reservoirs can be included in the river network.)

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☑ yes	☐ no
substantially altered hydrology due to urbanization	☐ yes	☐ no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☐ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☑ no
flexible in its licensing requirements	☐ yes	☑ no

capable of transporting to variety of PC platforms ☑ yes ☐ no

source code available to potential users ☐ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ➢ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

In the early 1980's, with financial support from the Commission of the European Communities, three quasi-commercial consulting institutions in Europe, *viz*. the Danish Hydraulic Institute, the British Institute of Hydrology and the French consulting company SOGREAH, embarked on a joint project to develop "physically based, distributed," general-purpose hydrological computer model, later to be known as the Système Hydrologique Européen (SHE). The status of the model as of the mid-1980's is presented by Abbott et al. (1996a, 1996b).

MIKE-SHE is a modified and expanded version of SHE marketed by the Danish Hydraulic Institute (DHI). MIKE is the general designation for a series of commercial software products offered by the Danish Hydraulic Institute, including:

MIKE11 - One-dimensional hydrodynamic/transport model for application to rivers, channels and irrigation systems, including rainfall-runoff, water quality and two-layer flow modules

MIKE21 - Two dimensional (vertical-averaged) hydrodynamic/transport model for general application to: free surface flows, coastal waters and seas, estuaries, including capability for short-period wave modeling

MIKE 3 - Three-dimensional version of MIKE21, primarily applied to coastal environments

MIKE SHE - distributed, physically based hydrological modeling system, which, according to DHI, is applicable to a wide range of water resources problems related to surface and ground water management, pollutant loading and soil erosion

MIKE BASIN - A river network model for integrated river basin planning and management. It accommodates a basin wide representation of water availability, sector water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints. This model uses a Graphical User Interface, which links MIKE BASIN directly with customized ArcView GIS, and includes reservoir operations, water-demand scenarios, and economic links.

MIKE SHE consists of several modules depicting the complete terrestrial hydrological cycle:

ET: Evapotranspiration component
UZ: Unsaturated Zone flow component
SZ: Saturated zone flow component
OZ: Overland and Channel flow
IR: Irrigation

These are supplemented with several "extensions" to address:

AD - solute transport (advection/dispersion)
PT - particle tracking
ADM - adsorption/degradation
GM - geochemistry
BM - biological degradation

In addition, there is a pre- and post-processing user interface, MIKE SHE PP that includes the following capabilities:

Digitization of mapped contours, river system and areally distributed data
Interpolation routines to provide point values and grid averages
Graphical editing of 2-D data and river data
Graphical presentation of simulation results in full color graphics
Plots of the variations in space of a variable in any layer or along any line through the model
Plots of time series of any variable

MIKE-SHE is receiving increased attention in Europe, due in part to the need for a comprehensive, user-oriented GIS-based modeling system to deal with Europe's own watershed management problems, and in part to the aggressive marketing of the Danish Hydraulic Institute. A recent book, though titled *Distributed hydrological modeling* (Abbott and Refsgaard, 1996) is in fact a compilation of applications of MIKE-SHE. The literature on MIKE-SHE is dominated by the publications of its principal developers J.C. Refsgaard and M.B. Abbott.

Example applications of MIKE-SHE are presented by Refsgaard (1997) for the 440 km^2 Karup catchment in Denmark. A calibration and post-validation procedure was carried out for catchment discharge and piezometric heads at seven selected observation wells. When the validated model was subjected to further validation tests, using observations from three additional discharge sites and four additional wells located within the catchment, it showed significantly poorer results compared to the calibration/validation sites. Refsgaard also determined that for a catchment of this size, a maximum grid size of 1000 m should be used for simulations of discharge and ground-water heads, the results deteriorating with coarser model grids.

MIKE-SHE has recently been applied in Sweden to urban watershed modeling through a research project funded by the Swedish Water and Wastewater Works Association (Gustafsson et al., 1997). The project addressed extreme overflows due to large groundwater infiltration to the sewer network of Vittskoevle, a village outside the City of Kristianstad, Sweden. The authors state that the overall goal was to test if it is possible to describe the surrounding geohydrological processes and their interaction with the sewer network, similar to the way dynamic pipe flow modeling can give a detailed description of the hydraulics. The authors consider MIKE SHE to be verified successfully for the catchment. Simulations were then carried out in order to evaluate the effects from historical measures and alternative future alleviation schemes. The results indicate among others, that the construction of a new alternative drainage scheme would make it possible to reduce the inflow to the plant by as much as 75% without risk of increased groundwater levels.

While the GIS interface and the user-oriented input structure are strengths of the program, the underlying physical formulation has presented problems in some applications. Xevi et al. (1997) describe an application using the Neuenkirchen research catchment hydrologic characteristics and a two-year time series of stream flows at the outlet of the catchment. For the validation runs, the base flows were overestimated in the period of high rainfall intensity while the peak flows were reasonably matched. Peak overland flow and the total overland flow proved to be very sensitive to the flow resistance parameters and to the vertical hydraulic conductivity of the surface soil, while the peak aquifer discharge and the total aquifer discharge were sensitive to the horizontal hydraulic conductivity in the saturated zone. The model output variables considered by these authors were found to be neither affected to a significant extent by the vegetation parameters nor by the specific storage coefficient. Jayatilaka et al. (1998) report an application in the Tragowel Plains, Australia to a 9-ha experimental irrigation site with significant interaction between irrigation and groundwater drainage. While the model was successfully calibrated against observed piezometric levels, drain flow and soil moisture, the authors identified inadequacies of the model, particularly in depicting rapid flow variations through macropores due to swelling and cracking of soil.

Some information about DHI commercial products is given on the DHI Internet homepage at:

http://www.dhi.dk/index.htm

with particular information on software products and demonstration animations at:

http://www.dhi.dk/general/dhisoft.htm

After the initial development of SHE, the cooperating institutions have implemented their own model development and enhancement projects based upon SHE. In Great Britain, this work has continued at the Water Resource Systems Research Unit at the University of Newcastle upon Tyne. The current model product is referred to as SHETRAN, earlier SHESED (see Bathurst et al., 1995), information about which can be found at the Internet site:

http://www.ncl.ac.uk/wrgi/wrsrl/rbms/rbms.html#SHETRAN

This also is a commercial product, but it appears that the level of I/O sophistication through GUI software is not as far along as is the case for MIKESHE.

Model: **MODFLOW**

Source: U.S. Geological Survey
Hydrologic Analysis Software Support Program
437 National Center
Reston, VA 20192

Discussion

MODFLOW is the general three-dimensional groundwater model employed and promulgated by the USGS (Hill, 1992). Although on the list of models to be considered in this review, the model *per se* has little surface-water capability, and therefore no immediate role in a TMDL determination. The surface-water components of MODFLOW, such as they are, include a reservoir leakage module (Fenske et al., 1997) and a streamflow routing package (Swain and Wexler, 1992, Swain, 1993, 1994), but both of these are very simplistic and are used only to estimate the effects of these surface watercourses on the subsurface water.

Bissett and Poeter (1994) describe an application of MODFLOW with the Stream Package to determine the interaction between an aquifer and surface streams near Golden, Colorado. Interaction of groundwater with a wetlands system was simulated using MODFLOW by Bradley and Brown (1997) and by Restrepo et al. (1998). Swain et al. (1996) describe an application using these new capabilities to modeling an interacting wetlands-river-aquifer system in Dade County, Florida.

The model has been coupled with surface-water models for special-purpose applications. Fredericks and Labadie (1993) combined MODFLOW with a river-basin network model MODSIM to evaluate water-volume/flow interactions between surface and groundwater in the South Platte basin. Yan and Smith (1994) coupled MODFLOW with the South Florida Water Management Model (a surface-network model) to simulate surface-groundwater interactions. It is noteworthy that all of these applications involved surface-ground water volume (or flow) interactions, and none address water-quality. Some experimental work has been carried out coupling MODFLOW to GIS-based data systems, e.g. Orzol and McGrath (1989) and Tang and Kondoh (1996).

Model: **PHOSMOD (Phosphorus Model)**

Source: North American Lake Management Society (NALMS)
P.O. Box 5443
Madison, WI 53705

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

lakes and reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☐ yes	☑ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☐ yes	☑ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic	☑ yes	☐ no

Level-1 Screening:	☑ **eliminate**	☐ **consider**

Discussion

PHOSMOD was developed by Chapra (1991) about a decade ago, as a simplified method of determining phosphorus concentrations in a stratified lake subject to known loads. The model assumes a two-layer lake (epilimnion and hypolimnion), horizontally homogeneous, overlying a sediment compartment. The steady-state concentration of P in all three compartments is computed based on inputs from external loading and recycling from the sediments. The model includes parameterized terms for losses due to flushing and settling, and appears to be confined to physical conversions, i.e. in the sediment layer recycling and burial, in which recycling is driven by the P in the sediment and hypolimnetic oxygen concentration, in turn based upon an empirical model fitted to data from the real system.

There is no hydrodynamic or water-budget component to the model. The user must supply lake stratification periods and morphometry, initial lake total phosphorus, sediment parameters, initial hypolimnetic DO concentrations, settling and burial rates for sediments, and time series of flow and inflow phosphorus concentrations. (There is also needed the empirical model for hypolimnetic DO.) The model is basically an accounting routine for phosphorus, and is intended to be used only for long-term, rather coarse evaluations.

Relatively few applications of PHOSMOD have been reported in the literature. Chapra and Canale (1991) report an application to Shagawa Lake in Michigan. Yokom et al. (1997) describe an application to Twin City South, a mine pit lake in northern Minnesota. In this case, the model predictions were less than satisfactory, and the authors judge that the most important factors affecting the application of the model to this lake are the waste load characteristics, DO depletion, sediment P release and a high basin sedimentation rate.

PHOSMOD is available at a cost of $ 80 from NALMS, see the NALMS Internet homepage:

http://www.nalms.org/

This includes a 20-page user's manual. No information is available about the coding of the model, except that the program executes on older DOS systems, with tabular I/O, and has evidently not been updated. No information is given about restrictions on redistribution or availability of the source code.

While the utility of this model in the Texas TMDL process is doubtful, we note that there are many instances in Texas in which a simplified model of nutrient kinetics would be of value. Many Texas reservoirs exhibit the same seasonal progression of structure year after year. When there is such stability in the lake structure, the need for a hydrodynamic model (with its attendant complexity and data requirements) may be replaced by observational data for the purpose of evaluating nutrient kinetics. It might be beneficial for such a model to be developed using modern PC interface and display capabilities.

Model: **POM (Princeton Ocean Model)**

Source: Program in Atmospheric and Oceanic Sciences
Princeton University
Princeton, NJ 08544-0710

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

estuaries
coastal ocean
lakes & reservoirs

Representative of Texas hydrological systems and Texas hydroclimates:

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 4 Criteria specific to special-purpose estuary models

(1) Model formulation:

spatial depiction: ☐ one-dimensional longitudinal ☐ two-dimensional horizontal ☐ two-dimensional longitudinal-vertical ☑ three-dimensional

variable geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☐ time varying tidal-mean ☑ fully time varying

accommodates riverine hydrographs? ☑ yes ☐ no

includes gravitational circulation (density variation)? ☑ yes ☐ no

basis for current distribution: ☐ direct input ☐ continuity only ☐ separate hydrodynamic model ☑ integral hydrodynamic model ☐ other

water quality (mass transport) capability included? ☐ yes ☑ no

sediment dynamics in estuary included? ☐ yes ☑ no

peripheral sediment loads included? ☐ yes ☐ no

(2) Numerical solution:

method for numerical specification of estuary geometry:
☐ manual input ☐ import of standard files ☑ grid generator ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

for hydrodynamic models with coupled density, scale separation or mode-splitting?
☑ yes ☐ no

(3) Implementation for computer operation

Source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

Minimum hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Has the model been routinely flanged with a watershed model? ☐ yes ☐ no

Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ☑ yes ☐ no

(4) Suitability for Texas estuarine systems.

Demonstrated application to bays or estuaries typical of Texas? ☑ yes ☐ no

Acceptable performance in model validation studies? ☑ yes ☐ no

Acceptable level of technical acceptance? ☑ yes ☐ no

(5) Capability for implementation in a GIS environment.

Has model been operated with GIS derived inputs, either with or without an associated watershed model? ☑ yes ☐ no

Has model output been displayed using modern visualization capabilities?
☑ yes ☐ no

Discussion

The Princeton Ocean Model (POM) was originally designed to be a general-purpose model for hydrodynamic processes in the ocean environment, primarily to support research in the nearshore and shelf areas. It has become one of the leading models in the world for study of circulation in estuaries. POM has been validated to field data in many estuaries and coastal ocean regions. It has been more widely used, and therefore more widely validated, than any other three-dimensional coastal ocean model. The level of technical acceptance of POM among researchers in estuary processes is very high.

POM is one of the earliest of the "new family" of very general, hydrodynamically based three-dimensional coastal models that have begun to proliferate within the last decade, a consequence of the great strides in computing power and the hunger for dissertation topics. It was intended as a research tool, being coded in structured FORTRAN with open, modular programming to facility incorporation of user-written codes. The initial development of the model is described by Blumberg and Mellor (1987), though work on the model dated back a decade before this publication, and the model has been widely modified and enhanced since then. Similarly the user's guide has undergone many revisions, most recent (at this writing) being Mellor (1998).

POM is fully three-dimensional and employs a curvilinear coordinate system in the horizontal and "stretched" coordinate in the vertical (i.e., sigma coordinate). The physics embodied in the governing equations are completely general, subject to the constraints that the flow be hydrostatic, incompressible and turbulent. Diffusion is modeled by the Mellor-Yamada turbulence-closure scheme and bed friction is modeled by matching the vertical profile of horizontal current with a logarithmic-law profile parameterized by the roughness length z_o. A riverine system is specified in POM on an orthogonal curvilinear grid. Therefore the river is represented by a number of quadrilateral cells covering the area of the river. These quadrilaterals do not overlap and are arranged such that a line drawn between the centers of two adjacent cells approximately passes through the center of the side separating the two cells. The numerical method cannot handle rivers with floodplains. Also, there is no provision for flooding and de-watering of peripheral cells.

Although POM is very widely used and has a history of successful applications (e.g. Oey et al., 1985), the numerical method used in POM is not state-of-the-art. For example, an explicit timestep is used to update the water surface elevation, whose Courant limit requires that the solution be advanced only by a very small timestep, frequently less than one second. Therefore, the model can be less efficient than more recent models, such as EFDC (Hamrick, 1992). On the other hand, the vagaries of such methods are well-understood and when proper cognizance is taken to avoid instabilities, a valid solution is achieved. Some of the newer higher-order techniques, such as employed in EFDC, have been inadequately tested in full-scale applications.

The numerical method of POM can also cause simulations to fail due to computational instability or error accumulation. For this reason the model may require a fair amount of “tuning” to give stable and accurate results. POM uses a “mode-splitting” technique in which the depth-averaged currents are solved in the “external” (or barotropic) mode and vertical shears are computed in the “internal” (or baroclinic) mode. Such mode-splitting must be performed carefully, or interactive instabilities can result (e.g, Smith, 1997). In order to stabilize the solution and decrease oscillations, addition of dissipation by means of filtering or mixing coefficients may be required, which may in turn degrade the accuracy of the simulation. Though the use of stretched coordinates has a long use in geofluid modeling, it is interesting that Johnson et al. (1989) converted from sigma coordinates to z coordinates because they found that the use of sigma coordinates resulted in unphysical vertical mixing in their simulations.

The model is not "user friendly" nor was it intended to be. It was designed to be a tool for use by a knowledgeable and specialized researcher, and was intended to relieve the burden of "coding up" an advanced simulation model for studies of coastal circulation, thereby freeing the researcher to pursue advanced subjects of coastal oceanography without having to re-invent the wheel. Therefore, POM has less options and does not emphasize automation of inputs (in comparison to, say, the EFDC). In order to run POM a non-orthogonal curvilinear grid must be generated. A public domain program named “curvigrid” is available with POM (Mellor, 1998) and can be used to generate grids for POM. In addition to grid generation some basic input files must be created. However, unlike most models, modification of the source code to POM is required for most applications. For example, boundary conditions are specified in POM by modification of statements in the FORTRAN code (Mellor, 1998). Operation of the model clearly requires considerable expertise on the part of the user.

The standard version of POM, distributed by George Mellor (1998), does not include any sediment transport or water quality component. Thus, in a TMDL study that involved sediment transport or chemical reactions, the POM source code would need to be modified to include these processes or linked with a water quality model. The model does include a capability for modeling transport of *conservative* waterborne constituents. (Note that temperature and salinity fields are part of the model solution.) The transport method considers advection and diffusion or sub-grid scale dispersion. It does not have a capability for including chemical reactions, or physico-chemical sources or sinks or the constituent, nor is there any capability for coupling multiple constituents. (This is what is meant by a "water quality" capability.)

Because the model has a complete hydrodynamic and thermodynamic modeling capability, it can be applied as well to determining stratification and circulation in a lake, and has been successfully applied to lake environments. An example of a lake application is Kelley et al. (1998). POM is used for the Great Lakes Coastal Forecasting System by Ohio State University and the NOAA Great Lakes Environmental Lab for Lake Erie.

The model, user's manual, and a wealth of application information are available from the POM Internet homepage at:

http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/

This site includes an extensive bibliography of peer-reviewed literature documenting application and validation of the POM in a range of coastal settings. The reader is referred to this source for an extensive reference list. The research version of POM is freely available from the website. Because there are several proprietary versions of POM (a major staple of the consulting services provided by companies like Dynalysis of Princeton and Hydroqual), for many years the research version was restricted to use by educational institutions. With the widespread proliferation of POM, it became infeasible to control its distribution, and in September 1999, Princeton issued the decision that the model should be free to all users under the terms of the GNU General Public License.

As noted above, the model is coded in standard structured FORTRAN. The computer requirements of POM depend on the number of grid points used. High-resolution three-dimensional simulations using POM are very computationally intensive due to the large number of grid points involved and the small timestep used to advance the solution. An example of runtime given on the POM web-site is 1336 seconds for 1 day runtime on a grid of 65 by 49 by 21 cells, on a 333 MHz PentiumII, for which 2.8MW (megawords) of memory were used.

The standard model available from the POM web-site does not have the capability of coupling with other models. Such coupling would require modification of source code. However, since a large POM user base exists, a non-standard version that has been modified to have the desired coupling may be available. Because POM is in wide use, several non-standard versions exist and may be available from various POM users. Some information about these versions can be found on the FAQ (frequently asked questions) link on the POM web-site.

None of the literature reviewed in this study indicated a connection of POM to a GIS framework. Bathymetry, geometry, boundary conditions are critical model parameters for POM, specification of which would be facilitated by the spatial analysis capability of GIS. This would best be implemented as a "front-end" preprocessor, rather than being directly integrated into POM. Similarly, the generation of a curvilinear grid can be aided by the use of GIS – especially in the visualization of the final grid in relation to the modeled water body. (Many models require a front-end grid generation, and there is an increasing number of such generators on the market, for example GRIDPAK, see: http://marine.rutgers.edu/po/gridpak.html.)

Model: **PRMS (Precipitation-Runoff Modeling System)**

Source: US Geological Survey
Hydrological Analysis Software Support Program
437 National Center
Reston, VA 20192

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Watershed
Vadose-Zone/Groundwater

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☐ no
substantially altered hydrology due to urbanization	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
[PC executable version available]		
source code available to potential users	☑ yes	☐ no
[UNIX version only available]		

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria (watershed models)

(1) Model formulation

differentiation of soil types, vegetation, land-use? ☑ yes ☐ no

satisfactory determination of runoff? ☑ yes ☐ no

satisfactory disposition of surface flow? ☐ yes ☐ no

sediment mobilization & transport included? ☑ yes ☐ no

temporal integration: ☐ event only ☐ continuous

receiving water: ☐ included in model ☐ external link ☑ none

inclusion of features extraneous to Texas? ☑ yes ☐ no

(2) Numerical solution

method for numerical specification of terrain and drainage network:
☐ manual input ☐ import of standard files ☑ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Level-2 Screening: ☐ **eliminate** ☑ **consider**

Discussion

The Precipitation-Runoff Modeling System is a third generation, FORTRAN 77-based, watershed model for the evaluation the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology. The model, which is a modular-design, distributed-parameter system, is developed and supported by the US Geological Survey. Basin responses to normal and extreme rainfall can be simulated to analyze the changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and groundwater recharge.

The concept behind the model is to divide a watershed into a series of homogeneous response units (HRUs) based on basin characteristics such as slope, aspect, elevation, vegetation type, soil type, land use and precipitation distribution. Use of HRUs was found to be more accurate than the approach used by HSPF in a study by Flugel (1995). The sum of the HRU responses, weighted by area, produces the daily system response and streamflow for a basin. The simulation of a storm hydrograph is also possible, along with groundwater and vadose zone flow.

PRMS allows spatial variability in soil type. Parameters or relationships that depend on soil type are included in the modeling of infiltration, evaporation and transpiration from the soil, subsurface flow and other watershed processes. Relationships for actual evapotranspiration are defined for three soil types: sand, loam and clay (Leavesley and Stannard, 1995). Vegetation cover parameters, which can be specified in each HRU, include vegetation cover density and the maximum storage available on this vegetation, which is a function of precipitation form (snow, winter rain or summer rain). Sediment detachment and transport is modeled using a rill-interrill concept approach (Leavesley and Stannard, 1995). Input requirements include the sediment concentration (mass/volume) and parameters controlling the rainfall detachment rate of sediment and the overland flow detachment rate of sediment.

The required inputs for streamflow computations are daily precipitation and daily maximum and minimum air temperature for each HRU (daily pan evaporation data can be substituted for temperature data). For a storm hydrograph and sediment computations, short time-interval precipitation, streamflow, and sediment data are needed. In relation to the land surface, topography, soils and vegetation for each HRU need to be supplied. The output consists of a variety of options, including mean daily discharge, annual and monthly summaries of precipitation, interception, potential and actual evapotranspiration, and inflows and outflows of the groundwater and subsurface reservoirs.

PRMS is distributed in UNIX and PC-based forms, although it seems that the code is only available for the UNIX based program. No information was available as to whether the PC-based code could be obtained from USGS.

Input parameters required by PRMS include the following, needed for each HRU:

Climate Components:

- Daily precipitation
- Maximum and minimum air temperature
- Solar radiation
- Longwave radiation
- Lapse rate (for mountainous watersheds)
- Pan evaporation

Land Phase Components

- Seasonal cover density
- Maximum interception storage depth on vegetation

- Water-holding capacity of the soil-zone reservoir
- Ground-water reservoir storage
- Winter cover density for the predominant vegetation above the snowpack
- Hydraulic conductivity of the transmission zone
- Effective value of the product of capillary drive and moisture deficit at field capacity and wilting point

Channel and overland flow parameters

- Slope
- Surface roughness (friction coefficients)
- Parameters involving detachment rate of sediment

The number of parameters is quite large, but is certainly fewer than the number required by the HSPF model. Therefore, PRMS may be expected to be somewhat easier to use but also somewhat less general than HSPF.

The possible scales of temporal integration can be one day (daily averaged) or a storm-mode computation for which a time interval can be selected for integration. The spatial scales used are defined by the HRUs for the daily-averaged computations. Parameters within an HRU are constant but many HRUs can be defined to describe a watershed (e.g. Flugel 1995). For storm-mode computations additional spatial refinement is possible with a single HRU. Specifically, multiple flow planes can be defined in one HRU, to account for variable slope and surface roughness. All the flow planes discharge into channel segments that are linked to form a drainage network.

Different versions of the model have been used since 1979 (Leavesley and Striffler, 1979). It appears to be used quite widely and some detailed calibration/validation has been performed (e.g. Flugel 1995). Multiple publications of applications of PRMS are available in peer-reviewed publications, showing a good level of technical acceptance. In a comparison of PRMS and HSPF, Flugel (1995) concluded that PRMS was more effective for application to the drainage basin of the River Brol. Several examples of the application of PRMS have been reported in the recent literature. Most recently, the model was used in Wisconsin for the evaluation of urbanization on groundwater recharge and flood peaks (Steuer, 1999). Starting in 1990, the USGS has been conducting a study in the Upper Truckee River Basin, which utilized both PRMS to simulate inputs from the alpine watersheds to the stream channel and reservoir systems of the basins of interests (USGS, 1995, 1996).

Additional projects have focused on the connectivity of GIS to the PRMS modeling system through the generation of model inputs. These have included a study of the Willamette River Basin in Oregon where GIS was used to define land use, soils, geology, and topography for each HRU (Laenen and Risley, 1995). A similar project dealt with the actual delineation of HRUs by analyzing basin properties through GIS (Flugel, 1995). Also available is *Weasel*, a GIS-based analysis tool that is meant to assist the user in developing input for PRMS (Leavesley et al., 1997).

PRMS uses the same data-management front end as HSPF, *viz*. ANNIE to help users interactively store, retrieve, list, plot, check, and update spatial- and time-series data for hydrologic models, which in turn uses the Watershed Data Management (WDM) direct access file. The model incorporates the U.S. Weather Service's Extended Streamflow Prediction program. In addition the model code is written using a modular structure so that in principle it can be easily modified or coupled with other models.

In the past 5 years, attention has focused on the Modular Modeling System (MMS), a UNIX-based framework, which incorporates PRMS and other modeling components for optimum use. MMS has been developed to provide the framework needed to support the development, testing, and evaluation of physical-process algorithms and to facilitate integration of user-selected set of algorithms into operational physical-process models. MMS uses a master library that contains compatible modules for simulating a variety of water, energy, and biogeochemical processes. Depending on the system, different algorithms can be chosen to model the desired chemicals and responses. In addition, a GIS interface has been developed to aid in the use of the MMS (Leavesley and Stannard, 1995).

The model PRMS can be downloaded from the USGS Internet site:

http://water.usgs.gov/software/prms.html

Additional information, including example applications, can be found at:

http://smig.usgs.gov/SMIC/

PRMS has some serious deficiencies for its immediate use in TMDL determinations. Foremost is the lack of a capability for modeling transport of other waterborne constituents, particularly those derived from the landscape. A modeling system, the Modular Modeling System (MMS), is presently under development by USGS, which includes PRMS as well as TOPMODEL, and in the future may incorporate water-quality capability. Another deficiency is that the model is not set up to be coupled with a receiving water model. Possible limitations on the portability of the FORTRAN code represent yet another deficiency. At this point, therefore, PRMS cannot be considered a viable candidate for use in the Texas TMDL process. However, the model has many potential capabilities in the hydrological model representing an advance over HSPF and SWAT, and we recommend that the development and application of the PRMS model continue to be monitored.

Model: **QUAL2E (Enhanced Stream Quality Model)**

Source: Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
Environmental Research Laboratory
College Station Road
Athens, Georgia 30613

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry	☑ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☐ yes	☑ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ⋗ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria for stream/river models

(1) Model formulation

variable channel geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☑ steady-state only ☐ time varying

accommodates flood-type hydrograph? ☐ yes ☑ no

basis for current computation: ☑ direct input ☑ continuity only
☐ kinematic wave ☐ complete hydraulic model ☐ other

water quality (mass transport) capability included? ☑ yes ☐ no

sediment dynamics in stream included? ☐ yes ☑ no

peripheral sediment loads included? ☐ yes ☑ no

capability to include channel estuaries or run-of-river reservoirs? ☑ yes ☐ no

[Estuaries limited to shallow one-dimensional systems dominated by dispersion. Run of river reservoir limited to shallow nonstratified reservoir with low throughflow.]

(2) Numerical solution

method for numerical specification of stream channel and network:
☑ manual input ☐ import of standard files ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

has the model been routinely flanged with a watershed model? ☐ yes ☑ no

Level-2 Screening: ☐ **eliminate** ☑ **consider**

[Limited utility in TMDL problems, see Discussion below.]

Discussion

The Enhanced Stream Quality Model (QUAL2E) is distributed and supported by the U.S. Environmental Protection Agency, and is one of the models included in the TMDL shell BASINS. The foundation of QUAL2E was the one-dimensional stream-quality program QUAL developed by the Texas Water Development Board in the late 1960's, one of the first general-application models for use in a range of watercourses. The program has gone through significant revisions in the last 30 years.

QUAL2E is applicable to sectionally well-mixed, dendritic streams. The model includes the effects of advection, dispersion, dilution, constituent reactions and interactions, and sources and sinks (Brown and Barnwell, 1987). While there is some provision in QUAL2E for modeling a general nonconservative constituent, its main capabilities are in treating those parameters of primary concern in assessing the impacts to a watercourse of organic loads, mainly on the concentration of oxygen. The model therefore has built-in options to depict the major reactions of nutrient cycles, algal production, benthic and carbonaceous oxygen demand, and atmospheric reaeration.

The watercourse is discretized along its longitudinal axis as a series of computational "elements," which are grouped into reaches of no more than 20 elements. (The maximum allowable number of reaches is 50.) Computations are carried out for constituent concentrations at each element, using a finite-difference solution of the advection-dispersion equation with various source and sink terms. Grouping by reach facilitates the input process, in that the major transport terms and reaction coefficients are considered to be constant within each reach. Branching watercourses, i.e. tributary drainage, can be depicted (with up to ten separate branches).

There are seven distinct computational elements within QUAL2E:

standard	headwater
element upstream from a junction	junction
input element	withdrawal element
last element in system	

Headwater elements are the upstream termini of every tributary and of the main river system. A junction element is the confluence of a tributary branch, and the last element is the downstream terminus of the modeled reach of the river. The input and withdrawal element types represent inputs (waste load and/or flow). Major tributaries would most likely be depicted explicitly as branches in the model system. However, smaller tributaries can be addressed by defining them as an inflow (or negative withdrawal) element, which reduces the complexity of the schematized system.

Some confusion has resulted from dissemination of the description in the user's manual (e.g., Brown and Barnwell, 1987) that "QUAL2E can operate either as a steady-state or as a dynamic model." This is not an accurate statement of the time-modeling capability of QUAL2E. The limit to dynamic capabilities of QUAL2E is depiction of the diurnal cycle of oxygen solubility and photosynthesis production, which is based upon diel patterns of solar radiation and temperature. In all other respects, *QUAL2E is a steady-state model*. In fact, the basic mass conservation equation in QUAL2E sets the time derivative to zero *identically*, $\partial c/\partial t = 0$, and the resulting tri-diagonal finite-difference equation is solved directly by Gaussian elimination.

The model can be converted to a time-varying model, but this requires substantial re-programming, and there is no publicly disseminated version with this capability. Walton and Webb (1994) modified QUAL2E to treat the dynamic event of pulse-input loads from combined sewer overflows, by modifying the advective numerical scheme. Application of the model was illustrated by a combined sewer overflow study on the Charles and Mystic Rivers in Boston, Massachusetts. Tolman (1992) modified QUAL2E to account for time variable headwater conditions and the photosynthesis and respiration of attached aquatic plants.

Input requirements for a full system run (i.e., all constituents modeled) include parameters that describe chemical, biological, and physical interactions. The data requirements of QUAL2E are moderate, as such models go, and include headwater conditions for the constituents being modeled, boundary inputs, temperature, incremental flow, and chemical constants and parameters. Bed characteristics are defined by Manning's n and channel slope. The model allows for multiple pollutant inputs, withdrawals, tributary flows and incremental inflow and outflow. These can be nonpoint sources, in that the model includes the option that these loads be injected uniformly along the length of a reach, but still the loads must be constant in time. In addition, QUAL2E includes a capability to compute required dilution flows for augmentation to meet a desired DO level. QUAL2E does not have a capability for modeling sediment and sedimentary processes *per se*, though it does include some sediment flux terms in the submodels for nutrients, organics and DO.

The major transport mechanisms of advection and dispersion operate along the main longitudinal direction of flow. QUAL2E does not include a hydrodynamic component, and the flows must be supplied by the user. Since the flow regime is assumed to be steady state, the flow in the stream channel is equal to the (algebraic) sum of flows across the water-surface boundaries, predominantly the flows through the upstream and downstream ends. The user also supplies power-law relations giving one of section-mean current or cross sectional area as a function of Q (from which the other is calculated, since Q = uA) and mean water depth as a function of Q. In addition, dispersion coefficients are supplied by the user.

Dissolved oxygen is perhaps the most important modeled constituent within QUAL2E, and most of its history of application is in addressing DO problems. Inputs for DO include saturation concentration, rates of O_2 production and uptake due to algae, chemical oxidation, sediment oxygen demand rate, and reaeration rate. Much emphasis is placed on the reaeration rate (eight possible options).

QUAL2E models the nutrient cycle, including temperature, chlorophyll-a (as a proxy for algae), organic nitrogen, ammonia, nitrite, nitrate, organic phosphorous, dissolved phosphorous, CBOD, DO, coliforms, an arbitrary nonconservative constituent, and three conservative constituents. The basis for the simulation of the modeled constituents is the mass balance equation. For each reach, a hydrologic balance, a heat balance, and a material (i.e. concentration) balance are written. Mass is gained or lost from the computational element by transport processes, wastewater discharges and withdrawals. Mass can also be added or subtracted by internal processes such as release of mass from benthic source or biological transformations.

Algae biomass (chlorophyll-a) modeling requires that respiration rate, growth rate, light relationships, and nutrient relationships be quantified within the parameterization of the model. Many of the standard relationships are already coded into QUAL2E and the user can select the most accurate option within the input file. For example, the mathematical relationships between algal growth and light can be specified by using one of three pre-programmed options: half-saturation (Michaelis-Menten) method, Smith's function, or Steele's equations (Brown and Barnwell, 1987). The nitrogen cycle requires constants to parameterize temperature dependencies, nitrogen uptake by algae, organic nitrogen settling, and coefficients to specify the transformation of one form of nitrogen to another. The phosphorous cycle is very similar, also requiring algae respiration rates, temperature dependencies, and transformation coefficients. The model assumes a first order reaction to describe deoxygenation of CBOD in the stream. Other BOD sinks include sedimentation, scour and flocculation. The input constants required include deoxygenation rate, loss rate of BOD due to settling, and, if necessary, the conversion rate coefficient for converting 5-day BOD to ultimate BOD.

The intended application of QUAL2E is to the stream or river at a scale such that only the longitudinal variation of parameters is of importance. The extent to which an estuary or reservoir can be addressed within this sort of geometry is limited. The model has been applied to the tidal reach and salinity-intrusion reach of channel estuaries. It is necessary in these cases to use inflated dispersion coefficients to depict the effect of these hydrodynamic factors on the upstream transport of materials, see Ward and Montague (1996). We note that WASP has the same problem in this sort of application.

It would be difficult to generalize this model to the lake environment, mainly due to the model assumption that the primary transport mechanisms are significant in only one direction. To the extent that a run-of-the-river reservoir can be depicted as a one-dimensional longitudinally dominated system, QUAL2E could be used to model its quality. But the fact that QUAL2E has no vertical-resolution capability would limit its potential use to a shallow dendritic system, or perhaps to the epilimnion of a deeper system, provided that the hypolimnion is effectively de-coupled from the reservoir during the summer stratification. Moreover, for QUAL2E to be applied meaningfully, there would have to be a longitudinal current, due, say, to constant reservoir releases (for downstream water supply, for example). Otherwise, the longitudinal mixing would be dominated by dispersion (which is a user input).

QUAL2E has been applied to many watercourses throughout the United States. Macaitis and Johnson (1993) recently described an application of QUAL2E to the Chicago waterway and Upper Illinois waterway. It was calibrated and verified under flows ranging from 2,500to 3,800 cfs in the Chicago waterway at Lockport, and flows ranging from 5,200 to 15,800 cfs in the Upper Illinois waterway at Chillicothe, and found to be capable of predicting CBOD, dissolved oxygen, ammonia-nitrogen and orthophosphate within 10 to 20% percent of measured values at a 95 percent confidence interval. Extensive QUAL2E studies of DO/BOD and nutrients have been performed on rivers in New Jersey (Van Orden and Uchrin, 1993 and Melching and Yoon, 1996). Tsihrintzis et al. (1995) used QUAL2E to model a slow flowing canal in Tampa, Florida, calibrating the model against water quality field data. They report "fairly good agreement" between observed and predicted values for dissolved oxygen, organic nitrogen, and other parameters. Tillman and Dortch (1993) applied a modified version of QUAL2E to the lower

Missouri River to evaluate the effects of reducing release flows from Gavins Point Dam, the model being calibrated and verified using field data, which required inclusion of algae as a state variable.

USGS applied QUAL2E to modeling DO in the Salt Creek watershed in northeastern Illinois (Melching and Chang, 1996), comparing the model against two independent diel surveys conducted by Illinois Environmental Protection Agency (IEPA). A survey in August 1995 was intended to serve as calibration data, and one in June 1995 as verification. Data included in-stream measurements of sediment oxygen demand rates and carbonaceous biochemical oxygen demand (CBOD) decay rates by the IEPA and travel time and reaeration-rate coefficients by the U.S. Geological Survey. Additional adjustment proved necessary to better simulate constituent concentrations measured during the June 1995 diel survey, leading to two versions of the QUAL2E model: the model calibrated to the August 1995 survey, and the model further adjusted to the June 1995 survey.

The model has also been applied in TMDL studies, including a pollutant loading capacity analysis of the Colville River in Washington (Pelletier 1997). QUAL2E is part of the modeling framework developed to determine phosphorus loadings to Lake Okeechobee from watersheds located north of the lake (Wagner et al., 1996), which couples a modified version of CREAMS to the in-stream transport model QUAL2E. Hydraulics and water quality routines were modified to account for flow routing and phosphorus retention in both wetlands and stream channels. Calibration and verification of QUAL2E (driven by CREAMS output) were considered satisfactory.

In recent years, the model has also found international application in a range of hydroclimatological settings. Cubillo et al. (1992) applied QUAL2E to the major rivers of the Comunidadde Madrid in Spain, in which the model was calibrated and verified. Drolc and Koncan (1996) report calibration and verification of QUAL2E to the river Sava near Ljubljana, Slovenia, which exhibits DO problems due to municipal discharges. Shallcross and Mercer (1995) applied QUAL2EU to the Rio Tiete and Billings Reservoir system for Sao Paulo, Brazil, determining that the large amount of uncollected and untreated sewage throughout the basin would require greater levels of treatment or instream aeration.

QUAL2E was used to evaluate water quality in the Nalon, Caudal and Nora Rivers in Asturias, Spain (Tejero et al., 1993). Calibrating and validating the models were done by specific field studies. A combination of modeling and analysis of field data led to detection of specific processes, such as nitrification in the Nalon River, including processes not in the model, e.g. precipitation of P dissolved by seepage from quarries, denitrification by the anaerobic bed of the river, and increase in turbidity due to suspended carbon. Ciravolo et al. (1997) applied QUAL2E to the Simeto river basin (Sicily), but lacked water quality data for its evaluation. A modeling study using QUAL2E of the Mapocho River, Chile, was used to evaluate a remediation plan of wastewater treatment plants and imposition of irrigation water quality standards (Dussaillant et al., 1997). Data from a long period of low flows was used to calibrate the model. Ghosh and McBean (1998) report an application of QUAL2E to the Kali River in India, with emphasis on dry season conditions.

The model has become popular as a basis for generic modeling studies, which frequently provide insight into limitations of modeling. For example, Little and Williams (1992) used QUAL2E to demonstrate a nonlinear regression technique for calibration, using nonlinear programming to minimize the sum of squares of model errors. Six parameters were simultaneously estimated for two intensive survey data sets. The optimal parameter estimates were found to be considerably different for each data set. Cardwell and Ellis (1991) used model outputs to define a "discrete state-space" of incremental DO concentrations and BOD loads, then applied dynamic programming to determine the optimal combinations for each of 3 models: WASP, QUAL2E and Streeter-Phelps, using data for the Schuylkill River. Presumably, the same physical data was input to the models (flow and point source loads). Different optimal solutions were found for the three models, but no indication given for the source of the discrepancy.

Melching and Yoon (1996) evaluated sources of "uncertainty" (i.e., sensitivity) in a QUAL2E application to DO in the Passaic River in New Jersey, finding that in this case only the algal maximum-specific-growth rate and reaeration rate contribute significant uncertainty to model prediction. Warwick and Roberts (1992) embedded QUAL-TX in a Monte Carlo framework, to evaluate the risk of failing to meet an established in-stream DO criterion, which they found may be as high as 96%. The uncertainty associated with estimation of the future total Kjeldahl nitrogen concentration for a single tributary was found to have the greatest impact on the determination of allowable WWTP loadings.

QUAL2E has often been part of a larger modeling/management framework, frequently taking advantage of modern computer processing and visualization tools. The UC Davis Water Resources Modeling Group (Breithaupt et al., 1993, De George et al., 1993) developed a Windows GUI for QUAL2E applied to the Russian River, California, which is reported to have streamlined the processes of calibration and verification. In the Madrid application of Cubillo et al. (1992), a GUI specific to the Madrid network was written. Bureau of Reclamation (Cheney, 1993) has combined the Hydrologic River Operation Study System (HYDROSS) model with QUAL2E to treat flow and quality issues on the Flathead River. A GUI was developed to facilitate model application. The integration of QUAL2E into a decision support system with numerous models was shown with the Danube Emissions Management Decision Support System (DEMDESS, Bondelid, 1996). Currently, the USEPA has integrated QUAL2E into its ArcView based application: BASINS, which is meant to assist communities in the development of TMDLs. In addition, other user interfaces to QUAL2E have been developed to assist modelers in generating input decks, running the model, and displaying the output (Rodriguez and Barnwell, 1992), summarized below

The source code for QUAL2E is FORTRAN, and the model can be operated on a rather modest PC-compatible platform. The manual for QUAL2E indicates that it requires a PC with 256 K of RAM. This manual, though, is old and may not be updated to reflect the current version's requirements. It is probably safe to assume that QUAL2E would operate well on a 286 PC having a math coprocessor and at least 1 MG of RAM. In addition, current versions of the model also include a Windows interface, which requires a 386 computer with 4 M RAM and 10 M of harddisk space. The model and documentation can be downloaded from the EPA CEAM website:

ftp://ftp.epa.gov/epa_ceam/wwwhtml/qual2eu.htm http://www.epa.gov/ORD/WebPubs/QUAL2E/

The code itself is a throwback to the days of mainframe computers: the input format is that of 80-column punched cards. The most recent manual available on the EPA CEAM Internet site is Brown and Barnwell (1987), the product of a cooperative agreement between Tufts University and the EPA Environmental Research Laboratory. But in the last few years, QUAL2E has been provided with an interactive preprocessor (AQUAL) and a post-processor (Q2PLOT) to facilitate set-up and operation of the model on the PC. QUAL2EU includes capability for automated sensitivity analysis of various model parameters and a Monte Carlo procedure to determine error propagation (referred to in the model documentation as "uncertainty" analysis).

Recently a WINDOWS interface for QUAL2E has been developed (EPA, 1995) and may be downloaded from the EPA site:

http://www.epa.gov/OST/QUAL2E_WINDOWS/

This employs a series of windows to guide the user through the model set-up and execution tasks. The interface is designed to operate under Windows 3.1, Windows 95 and Windows 98, but does not operate under Windows NT.

The Windows interface assists the user in developing an accurate input block for the reach delineation. However, some manual segmentation of the river is necessary to get reach lengths and accurate river miles for point source, withdrawal and junction element locations – this part of the input generation could be facilitated by GIS. Currently, QUAL2E is integrated into EPA's BASINS, which is operated completely within the GIS software, ArcView 3.x. GIS assists the user in developing the input files, setting the model parameters, running the model and displaying the output.

The input for QUAL2E is contained within a number of text files generated by a text editor or the Windows interface. Changing parameters, constants, or other information within these files is relatively straightforward, as long as the use maintains the correct file formatting and spacing. Input for the reach representation includes river mile/kilometer of the head and end of reach, the geometric features (slope and bed characteristics), the types of computational elements within each reach and their location, and the incremental flows occurring at each element. Currently, the model is limited to 50 reaches with no more than 20 computational elements per reach (a maximum of 500). In addition, the model allows for no more than 10 headwater elements, 9 junction elements, and 50 point source or withdrawal elements – however, it seems that these limitations may be possibly overcome by re-dimensioning some arrays within the model code.

The potential utility for QUAL2E in the Texas TMDL process is ambiguous. Currently, QUAL2E is integrated into EPA's BASINS, where it couples with a watershed model comparable to HSPF called NPSM. (A review of QUAL2E within the BASINS framework is given in Ward and Benaman, 1999.) Thus, its use is *prima facie* promoted by EPA. The steady-state formulation of QUAL2E means that dynamic loading cannot be depicted, and this prohibits its use with dynamic non-point source watershed models. TMDL determination, however, includes consideration of both point and nonpoint loadings under a variety of critical conditions, and in many of Texas watercourses this will include point-source-dominated summer low-flow water quality. For this regime, QUAL2E is appropriate. Moreover, there may be systems in which runoff events with nonpoint-derived sources store contaminants in reservoirs or in the bed sediments of streams, resulting in deleterious water quality later under low-flow poorly aerated conditions. Here, QUAL2E may again be the appropriate model whose source/sink terms are imported from a watershed-loading model. Even in these cases, however, the State of Texas has developed and routinely applies a closely related model, QUAL-TX (see review following), which may be the better choice between the two.

Model: **QUALTX (Stream water quality model, Texas)**

Source: Texas Natural Resource Conservation Commission
Austin, TX 78711

[Level-1 screening identical to QUAL2E.]

Level-1 Screening: ☐ **eliminate** ☑ **consider**

[Level-2 screening identical to QUAL2E.]

Level-2 Screening: ☐ **eliminate** ☑ **consider**

[Limited utility in TMDL problems, see Discussion below.]

Discussion

QUALTX is applicable to sectionally well-mixed, dendritic streams and rivers. The foundation of QUALTX was the one-dimensional stream-quality program QUAL developed by the Texas Water Development Board in the late 1960's, one of the first general-application models for use in a range of watercourses. QUAL was also the predecessor of the EPA model QUAL2E. The two models QUALTX and QUAL2E are closely related. For that reason, the Level-1 and Level-2 screenings are identical, and the reader is referred to the review of QUAL2E for this information.

The main capabilities of QUALTX are in treating those parameters of primary concern in assessing the impacts to a watercourse of organic loads, mainly on the concentration of oxygen. The model has been widely used in Texas for determining DO impacts of a proposed or existing organic load, and has therefore figured centrally in the State's waste-load evaluation procedures.

As is the case for QUAL2E, QUALTX treats a river system as a branching one-dimensional network. Discretization in QUALTX and QUAL2E is identical, the longitudinal axis being represented as a series of computational "elements," which are grouped into "reaches" to facilitate input of constant parameters. Computations are carried out for constituent concentrations at each element, using a finite-difference solution of the advection-dispersion equation with various source and sink terms. As is the case with QUAL2E, QUALTX is a steady-state model. The basic mass conservation equation in QUALTX has a zero time derivative term, $\partial c/\partial t = 0$, and the resulting tri-diagonal finite-difference equation is solved directly by Gaussian elimination.

QUALTX does not include a hydrodynamic component, but the flows must be supplied by the user. The user also supplies power-law relations giving one of section-mean current or cross sectional area as a function of Q (from which the other is calculated, since Q = uA) and mean water depth as a function of Q. QUALTX provides for multiple pollutant inputs, withdrawals, tributary flows and incremental inflow and outflow. These can be nonpoint sources, in that the model includes the option that these loads be injected uniformly along the length of a reach, but still the loads must be constant in time. QUALTX does not have a capability for modeling sedimentary processes *per se*, though it does include some sediment flux terms in the submodels for nutrients, organics and DO.

The formulation and model operation of QUALTX are essentially identical to QUAL2E, and the reports of model application in the literature apply as well to QUALTX, so these aspects of the model are not discussed here, but reference is made to the preceding review of QUAL2E.

This review has not sought to determine at precisely what point the two models began to diverge in their evolution. Both are, however, coded in structured FORTRAN with a number of subroutine modules, some of which clearly correspond between the two models. Table 1 compares the two model structures, indicating which subroutines are common to both models. The current version of QUAL2E is adapted to the PC environment, with direct user-interactive screens, while QUALTX is operated in a batch mode, once the input deck is structured by the user. Thus, the program MAIN of QUALTX has been replaced by DRIVER and DOS in QUAL2E (the latter being unrelated to the subroutine DOS in QUALTX, which sets source and sink reactions for DO).

The comparison of Table 3-1 shows that QUAL2E is presently composed of 84 subroutine modules compared to 35 for QUALTX. Approximately 18 of these subroutines appear to directly correspond (we have not carried out a detailed study of all 119 subroutines), but even at that the QUAL2E subroutines are generally 60% longer than the corresponding QUALTX subroutine. This quantifies the fact that QUAL2E has a broader array of capabilities than QUALTX, to extend it to national and international locations (including, for example, the ability to compute ice cover on the river), more detail in its eutrophication and nutrient kinetics, and a series of operations to automate sensitivity analyses and perform error propagation analysis. On the other hand, QUALTX is specifically applicable to Texas watercourses, and includes capabilities such as the "Texas equation" for stream reaeration (developed from specific field measurements of aeration in Texas streams) and Texas-appropriate hydraulic relations.

Both QUAL2E and QUALTX have evolved from the antediluvian QUAL, and a comparison with the modern evolutionary products of early reptilian forms comes immediately to mind. While there are physiological similarities between the two models, one of these has evolved into a crocodile, powerful and omnivorous in its capabilities for dealing with a range of water-quality concerns, but massive and slow moving. The other has become a bird, its range of capabilities limited to the Texas environment and to Texas water-quality issues, but within those limitations, it is highly successful, being light, mobile, and well-adapted.

The same limitations noted to the potential utility of QUAL2E in the Texas TMDL process apply as well to QUALTX. Its steady-state formulation precludes its use with non-point source watershed models governed by dynamic events. However, many of Texas TMDL's will include point-source-dominated summer low-flow water quality, for which QUALTX is appropriate. Moreover, there may be systems in which runoff-derived contaminants are stored in reservoirs or streambed sediments to degrade water quality later under low-flow, poorly aerated conditions. In these cases, QUALTX may be the appropriate model, with boundary flux terms based upon a watershed-loading model.

Table 3-1
Comparison of FORTRAN subprogram structure for QUAL2E and QUAL-TX codes

name	*size (b)*	*name*	*size (b)*
QUAL2EU code		***QUAL-TX code***	
ALGAES	2,866	ALGS	1,292
ANCS	2,773		
BLOCK	10,767		
BLOCKUNC	11,816		
BODS	2,469	BODS	1,588
CHANL	3,059		
CLRSCR	279		
COLIS	2,447	COLIS	1,366
		COMMON	4,135
CONSVT	2,560	CONSS	1,081
DATSAV	1,846		
DBUG	1,850		
DOS	8,492		
		DOS	1,985
DRIVER	414		
FDES	7,353		
FLOAUG	9,865	FLOAUG	4,359
FOEA	9,670		
GETMSG	950		
		GRAPH	4,312
GROW	4,060	GROW	872
HEATER	7,109	HEATER	4,122
HEATEX	8,511		
HYDRAU	4,042	HYDRAU	4,053
IFOAMC	8,146		
IND00	3,530		
IND01	6,252		
IND02	3,501		
IND03	2,515		
IND04	4,025		
IND05	9,401		
IND06	7,569		
IND07	5,057		
IND08	4,607		
IND09	2,569		
IND10	5,227		

(continued)

Table 3-1
(continued)

name	*size (b)*	*name*	*size (b)*
QUAL2EU code		***QUAL-TX code***	
IND11	6,172		
IND12	2,240		
IND13	4,178		
IND1A	8,414		
		IN1DAT	20,042
		IN2DAT	22,658
		IN3DAT	16,100
		IN4DAT	13,528
INDATA	5,362	INDATA	3,713
INIT	5,290		
INSENS	6,150		
LIGHT	551		
		MAIN	24,486
		MAXCRD	605
MCSIM	7,218		
		NCMS	1,408
NH2NO3	1,738		
NH3S	2,916	NH3S	1,887
NO2S	2,437		
NO3S	2,460	NO3S	1,809
NRGEN	1,217		
OMATCH	5,550		
		ORGNS	1,433
ORGPO4	1,745		
PO4S	2,653	PO4S	1,686
PRPLOT	6,756	PRPLOT	7,952
PRTMSG	1,204		
PURGE	2,008		
Q2E3P1	30,065		
Q2EZ	7,054		
Q2U3P1	32,248		
QCALC1	1,450		
QCALC2	3,558		
QL2SMG	18,653		
RAND	3,479		
RANDVR	660		

(continued)

Table 3-1
(continued)

name	size (b)	name	size (b)
QUAL2EU code		***QUAL-TX code***	
REAERC	5,031	REAERC	3,110
RSTOR	5,861	RPTC	1,402
		RPTF	16,416
		RPTI	2,997
		RPTL	11,841
		RPTS	266
SENS	11,628		
SETUP	5,791		
		SOLAR	3,737
SOVMAT	3,913	SOVMAT	2,314
SSCONV	5,660		
SUBTS2	257		
SUBTST	257		
SWAP	6,217		
TCALCS	4,804		
TEMPS	3,376	TEMPS	1,981
TEMPSS	4,776		
TRIMAT	3,063	TRIMAT	4,023
UECHO	3,700		
UNCAS	5,312		
UNDATA	7,821		
		UNITS	1,541
URPT3	4,750		
WRPT1	4,813		
WRPT2	3,548		
WRPT3A	11,530		
WRPT3B	9,138		
WRPTI	1,998		
ZEROP	2,503		

Model: **RIVER3**

Source: Geological Survey of Canada
Natural Resources Canada
Bedford Institute of Oceanography
Dartmouth, NS, Canada

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Rivers and streams

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

RIVER3 is the latest incarnation of a hydrological/sediment transport model for streams and rivers developed by the Geological Survey of Canada. It is written in FORTRAN and the source code is made freely available by GSC. (The code is given in the appendix to Syvitski and Alcott, 1995.) The sediment loadings must be input by empirical rating curves, while re-mobilization and transport within the river channel are treated by standard relations (e.g., the Bagnold bedload formula). Recent additions include groundwater-driven baseflow (Syvitski and Alcott, 1995). The model has no capability for other water quality parameters.

While the model offers some promise for modeling sediment-laden streams, the range of its application has thus far been to high latitudes. Suitability for Texas climates is dubious, and much of the code (regarding water-substance transformations) is irrelevant to the Texas environment.

Model: **RIVMOD (Riverine Hydrodynamic Model)**

Source: Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
Environmental Research Laboratory
College Station Road
Athens, Georgia 30613

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Rivers and streams

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☑ yes	☐ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

RIVMOD evolved from a model developed in the early 1970's by Prof. M. Amein (e.g., Amein and Fong, 1970; Amein and Chu, 1975), and was re-coded around 1990 by a group at Law Engineering, see Hosseinipour et al. (1995). The model is a time-varying solution to the equations of momentum and continuity for a one-dimensional (section-mean) unidirectional river, *viz*. the St. Venant equations. It was intended to offer a time-dynamic option to the steady-state model QUAL2E, and has been "soft-linked" to WASP and SWMM. The model is distributed by EPA through CEAM, but its status is unclear. (It is not one of the models provided for routine download on the CEAM Internet site.)

The model has no transport capability, and is clearly intended to provide the hydrodynamic (i.e. advective) terms for a general transport model. Very few applications of the model were located in the recent literature. Wool et al. (1994) describe a modeling linkage of SWMM, RIVMOD and WASP for evaluation of watershed-derived loadings. Heim and Warwick (1997) used a WASP5-RIVMOD link to model transport of sediment in the Carson River, Nevada, and long-term transport of sediment into Lahontan Reservoir and transport of sediment into the reservoir during a flood year. (This was a major loading problem because of mercury-contaminated sediments from mine tailings of the Comstock Lode.)

The model is coded in FORTRAN. A commercial version of RIVMOD with a Windows interface is available for purchase from:

AScI Corporation
1365 Beverly Road
McLean, VA 22101

Model: **RUSLE (Revised Universal Soil Loss Equation)**

Source: Southwest Watershed Research Center
USDA - ARS
2000 East Allen Road
Tucson, AZ 85719

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

field, very small watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☐ yes ☑ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

Although the Revised Universal Soil Loss Equation (RUSLE) is a stand-alone model for the PC platform, from the viewpoint of this review it is in fact a sub-model, that is, a component that could be integrated into more comprehensive watershed models. It is, however, referenced in the recent literature, and forms an optional component of WEPP, so a brief description is included in this review.

The model is developed and promulgated by USDA as the most recent in the USLE methodology (Renard et al., 1977). The primary changes in the RUSLE, relative to USLE, are (1) a slight reformulation of R to better reflect storm "energy", (2) a more accurate estimate of LS, incorporating effects of surface residues, decreasing infiltration over the course of a storm, converging and diverging terrain, deposition on the watershed, and (3) implementation in a computer program, rather than the nomographs and look-up tables used by USLE.

Renard and Ferreira (1993) describe the computer-based RUSLE model, which employs "new relationships to estimate values of the six factors in the equation." Three input databases are required: climatic data, crop data, and field operations data. The enhanced RUSLE routines were incorporated into AGNPS by Needham and Young (1993), who named the resulting code ANN-AGNPS, since it was designed to compute annualized runoff (as opposed to the "event" simulations for which AGNPS is used). The model is "cellular based" with all characteristic inputs and calculations made at the cell level. The model is designed for agricultural applications, and only one comparison to a single storm event was reported, though its validation can be expected to be equivalent the USLE, which it replaces.

The model is disseminated by request from the Southwest Water Research Center. The code is written in C, and it is not clear whether SWRC will provide the source code itself to interested users.

Model: **SLAMM (Source Loading and Management Model)**

Source: Wisconsin District Office
U.S. Geological Survey
8505 Research Way
Middleton, WI 53562-3586

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☑ yes	☐ no
substantially altered hydrology due to urbanization	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	❑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

SLAMM is a model recently developed by the USGS for application to the urban settings of Wisconsin and similar northeastern areas. It has been placed within a GIS shell by other workers (Kim et al., 1993, Haubner and Joeres, 1996), but does not appear to presently have this construction in its official form. Its structure is simpler than SWMM, and it has fewer options for representing urban conditions, but it is therefore simpler to set-up and operate. (It does not, for example, include a point source capability, see Haubner and Joeres, 1996).

According to the USGS, SLAMM is "strongly based on actual field observations, with minimal reliance on theoretical processes that have not been adequately documented or confirmed in the field." Its use is described as "mostly" a planning tool, which appears to be an accurate summary of the limited published information. Its development placed emphasis on small frequency storms and the associated particulate and pollutant wash-off. USGS states, "SLAMM therefore incorporates unique process descriptions to more accurately predict the sources of runoff pollutants and flows for the storms of most interest in stormwater quality analyses." (It is not clear what this means.)

The basin to be modeled must be subdivided into elemental "lumped" watersheds by the user. (For example, Haubner and Joeres, 1996, scanned an engineering map of watershed boundaries to create this data layer.) Overlays of soils, land use and watershed boundaries create "homogeneous" polygons in the GIS. The runoff and contaminant loads from each such area are determined by empirical relations, then accumulated.

The literature on its application is thus far relatively sparse, because the model is a fairly recent development, and most citations describe its use in qualitative management decisions. For example, Kim et al. (1993) used the model to identify a "critical sewershed". The pollutant loadings at major sewer junctions were then estimated to establish a mitigation strategy, which turned out to be installation of wet ponds. They examined both a regional approach using a large area to build a wet pond at the major sewer outfalls, and a multi-site approach using a number of smaller sites for each major sewer junction. But no *evaluation* of model performance *per se* was offered. According to USGS, "SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rains, development characteristics, and control practices." But this statement is not borne out by the list of literature references provided in the model documentation.

The model is not available on the nationwide U.S.G.S. water-resources software Internet site, but may be obtained by download from the Wisconsin district homepage:

http://wi.water.USGS.Gov/slamm/

No information is available about the coding of the model, but since it is designed for execution on the PC platform, it is presumably written in C or BASIC. It is not clear whether the source code would be made available to a user.

Model: **SMPTOX (Simplified Method Program, variable-complexity stream Toxics model)**

Source: Environmental Protection Agency
Center for Exposure Assessment Modeling
960 College Station Road
Athens, GA 30605-2700

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Rivers and streams

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☐ yes	☑ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

SMPTOX is a family of one dimensional, steady-state mass balance models designed to incorporate sediment-water interactions into the kinetic terms. These models are capable in principle of predicting particulate and dissolved-phase non-ionic organic concentrations in water column and sediment, and require that the sediment be modeled as distinct layers.

The primary objective of these models is to simplify the modeling process. SMPTOX is limited to computing the effect of point-source discharges of "toxic" materials in a unidirectional stream or river. The program is designed for use in the waste allocation process, and includes pre- and post-processing to facilitate statistical comparisons to a specified standard or criterion.

No example applications could be found in the recent literature. The model is briefly described on the EPA model inventory page on the Internet:

http://www.epa.gov/OWOW/watershed/tools/model.html#5

The program itself is written in PASCAL, and both the source code and an executable for PC-compatible may be downloaded from:

ftp://ftp.epa.gov/epa_ceam/wwwhtml/smptox3.htm

A brief user’s manual and set-up guide (LTI, 1993) may also be downloaded from this site.

Model: **SPUR (Simulation of Productivity and Utilization of Rangelands)**

Source: Great Plains Systems Research Unit
USDA-ARS-NPA
P. O. Drawer E
301 S. Howes St.
Ft. Collins, CO 80522

Also: Texas Agricultural Experiment Station
P. O. Box 1658
Vernon, TX 76385

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☐ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

[inadequate information available]

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

The SPUR model has been under development by the USDA Agricultural Research Service since the early 1980's (Hanson et al., 1992). Its original purpose was to extend the methodology of CREAMS and EPIC to a rangeland (instead of an agricultural field) and to include the animal component in the model calculations. The general model structure and history are summarized by Carlson et al. (1995).

The model has gone through several versions, being tested against rangelands in Texas, and at every stage has been determined to be of limited accuracy (i.e., to perform poorly) compared to data. The original work was carried out in cooperation with the Department of Rangeland Ecology at Texas A&M University. The project has an Internet homepage at the site:

http://vernon.tamu.edu/taes/rlem/spur.htm

There appear to be two separate SPUR projects underway in the ARS. One is a cooperative effort between TAMU and the Great Plains Systems Research Unit, which expects to release

SPUR 2.4 in the near future. This will include more capability in soil organics than represented in SPUR91 (Carlson and Thurow, 1992).

The second effort is a project to incorporate SPUR into a GIS-based watershed model, being carried out at the Southwest Watershed Research Center of the USDA/ARS at Tuscon. The present emphasis of this project seems to be on hydrology and sediment transport with much more attention paid to process formulation, based upon experimental data from the Walnut Gulch Experimental Watershed. The model should have specific application for arid to semi-arid rangelands. There is a brief description of the project at the SWRC internet homepage at:

http://www.tucson.ars.ag.gov/research/modeling.html

Recent literature describing the model application seems to be confined to the work of the model developers, e.g. Carlson and Thurow (1996), Teague and Foy (1997). No information was located on the coding of the model (presumably in FORTRAN), or its availability.

Model: **SWAT (Soil and Water Assessment Tool)**

Source: Agricultural Research Service
U.S. Dept. of Agriculture
Grassland, Soil & Water Research Laboratory
808 East Blackland Road
Temple, TX 76502

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
lakes and reservoirs
vadose zone

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no

capable of transporting to variety of PC platforms ☑ yes ☐ no

source code available to potential users ☑ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Discussion

SWAT is the latest incarnation of a family of watershed models developed by the Agricultural Research Service of USDA extending back to CREAMS and ROTO (Routing Outputs to the Outlet). The immediate predecessor of SWAT is SWRRB, and the literature evaluations of SWRRB apply directly to SWAT as well. SWRRB is no longer supported by ARS, SWAT having taken its place.

The principle purpose of SWAT is computation of runoff and loadings from rural — especially agriculture dominated — watersheds (Williams and Arnold, 1993). The same geometric and physiographic depictions apply to SWAT as was the case with SWRRB, as do most of the model formulations, so the reader is referred to the discussion of SWRRB for this information (and a summary of input requirements). SWRRB was designed for application to a rather small watershed, which could be subdivided into no more than 10 subbasins. SWAT extends SWRRB by allowing multiple subbasins, up to 10,000. Not only does this permit more spatial resolution, it also allows SWAT to address larger watersheds than was the case for SWRRB. The model developers at BRC state that SWAT can be applied to watersheds of several thousand miles in area. An additional improvement in SWAT is the incorporation of better channel routing algorithms than used in SWRRB, the reach-routing approach of ROTO, in effect allowing more accurate interconnection of subbasins.

SWAT has continued to be improved by the modeling team at Blacklands Research Center. Among the recent improvements noted are incorporation of multiple hydrologic response units, inclusion of auto-fertilization and auto-irrigation as management options, addition of canopy storage of water, addition of a CO_2 component to crop growth components (for climatic change studies), addition of Penman-Monteith formula as option for potential evaporation, rewriting of lateral water flow using kinematic storage model, and in-stream nutrient kinetics added to channel routing equations. The capability for including impervious cover has been improved by adding urban build up/wash off equations (from SWMM). In the near future, the next release will include bacterial transport, improved rice/wetlands routines, and the addition of Green-Ampt infiltration formulae to the surface water budget.

Srinivasan and Arnold (1994) describe integration of SWAT into a GIS system for input data set development and model output visualization, reporting an application to a 114 sq. km upper subwatershed in the Seco Creek Basin. This watershed was subdivided into 37 subbasins for SWAT. They report the predicted average monthly streamflow to be in agreement with values derived from measurements. Bingner et al. (1997) made a specific study of subwatershed size dependency of SWAT, finding that runoff volume is not appreciably affected by the number and size of subwatersheds, but there is a definite lower (they say "upper") limit to subwatershed size, required to adequately simulate fine sediment yield produced from upland sources, in that decreasing the size of subwatersheds below this threshold does not substantially affect the computed fine sediment yield.

Applications of SWAT to several Texas river basins have been carried out by the Blackland Research Center (BRC), including the Lower Colorado, North Concho, and Trinity. The most ambitious recent application of SWAT in Texas is to the watershed of Lake Waco, including the Bosque River basin. The Bosque watershed is affected by numerous diary operations as well as row-crop agriculture and municipal waste discharges. A customized version of SWAT was created by incorporating subroutines and algorithms from APEX (yet another USDA-ARS agricultural water-management model) to better depict soluble P and N fluxes into soil and plants and to improve the modeling of BMP's (Best Management Practices, Clean-Water-Act patois for an array of structural or vegetational passive treatment strategies). Model coding was added to include filter stripping, inter-cropping, double-cropping and operation of lagoons. The model was also altered to accommodate point source inputs of N and P. The routing channel element of SWAT (see the description of SWRRB) was expanded to include rudimentary kinetics, to approximate biochemical reactions. This is not nearly as good as a *bona fide* stream model but at least subjects nonconservative water-quality parameters to a sort of kinetic process, and better depicts the transformation of nutrients along a stream channel.

The Lake Waco watershed was subdivided into 47 subbasins, organized into 7 basins, of which four (4) are main tributaries (North Bosque, Middle Mosque, South Bosque and Hog Creek) and three (3) are small peripheral catchments of the lake. The model was calibrated using the detailed flow and water quality data acquired by the TIAER program for 1993-97. This is the most comprehensive watershed data-collection program in the state. One of the key calibration parameters was the curve number, and BRC reduced the CN by 5 units throughout all the subbasins in order to achieve calibration versus monthly flows, typically within 20%. For sediment loads, the minimum C factor of the USLE (see Ward and Benaman, 1999) was doubled. Model simulations were carried out for a 38-year period, 1960-1997, and average loading rates determined over this time span. For all of its hydrological detail, SWAT is considered to be best applied to determining average loads over a long period of operation.

SWAT is coded in FORTRAN-90 and is transportable to a variety of platforms, including PC-compatibles. SWAT may be downloaded from the USDA Blacklands Research Center Internet site:

http://www.brc.tamus.edu/swat/

This is an extensive site with model documentation, example applications, and downloads of related products.

Model: **SWIM (Soil and Water Integrated Model)**

Source: Potsdam Institute for Climate Impact Research
P.O.Box 601203, Telegrafenberg
14412 Potsdam
Germany

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Watersheds

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☐ yes	☐ no
in public domain	☐ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

[no information available]

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

SWIM is a research model that is under development, see Krysanova et al. (1996, 1998). It is a GIS front-end using disaggregation methods of a European model (MATSALU) with the hydrology and crop simulations of SWAT. The developers (Krysanova et al., 1998) are applying this model to subbasins of the German Elbe. No information is available about the computer code, and it appears that use of SWIM is confined to Krysanova and colleagues.

Model: **SWMM (Storm Water Management Model)**

Source: Environmental Protection Agency
Center for Exposure Assessment Modeling
960 College Station Road
Athens, GA 30605-2700

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☐ yes	☑ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☑ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria (watershed models)

(1) Model formulation

differentiation of soil types, vegetation, land-use? ☑ yes ☐ no

satisfactory determination of runoff? ☑ yes ☐ no

satisfactory disposition of surface flow? ☑ yes ☐ no

sediment mobilization & transport included? ☐ yes ☑ no

temporal integration: ☐ event only ☑ continuous

receiving water: ☐ included in model ☐ external link ☑ none

inclusion of features extraneous to Texas? ☑ yes ☐ no

(2) Numerical solution

method for numerical specification of terrain and drainage network:
☑ manual input ☐ import of standard files ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Level-2 Screening: ☐ **eliminate** ☑ **consider**

Discussion

The Storm Water Management Model (SWMM) is a comprehensive water quantity and quality simulation model developed primarily for urban areas. The model has been widely used for analysis of hydrologic and hydraulic problems of both combined and separate sewer systems as well as for urban non-point pollution problems. SWMM was originally developed for the EPA in the period 1969-71 and was the first comprehensive model of its type for urban runoff analysis. Periodic improvements and updates have led to the current Version 4.3, which was completed in November 1993. SWMM has been used in scores of U.S. cities as well as in Canada and Europe. A summary of the model is given by Huber (1995) and more detail about its formulation is provided in the user's manuals (e.g., Huber and Dickinson, 1988, Huber et al., 1988).

SWMM simulates real storm events based on meteorological data and catchment, transport, storage, and treatment characterization. Model output consists of "quantity and quality" analysis, "quantity" being hydrographs and runoff volumes whereas "quality parameters" are pollutant loads. Single events and continuous simulations can be performed for any values of rainfall, runoff, and quality cycles for a watershed. However, the interstorm interval is treated simplistically, the most significant processes being continued infiltration into a base flow, and build-up of contaminants on impervious surfaces. By far, its most common—and successful—application is to isolated storm events. The model performs best in urbanized areas with impervious drainage, which was its original intended application, but it has been widely used elsewhere. Although developed for urban areas, SWMM can be applied in some watersheds with a non-urban composition.

SWMM is structured in the form of six modules or "blocks", which can be run together or independently. The blocks relating to the model *per se* are:

RAIN	-	processes precipitation data for input into RUNOFF block
TEMP	-	processes air temperature data for snowmelt computations
RUNOFF	-	generates runoff volume and quality from rain on watershed
TRANSPORT	-	kinematic wave routing of flow and quality, base flow generation, infiltration
STORAGE/ TREATMENT	-	detention
EXTRAN (EXTENDED TRANSPORT)	-	Dynamic routing

SWMM does not include a block for analysis of receiving water quality (at one time the XTRAN block provided this capability, Huber et al., 1988), but has been directly interfaced with EPA's WASP receiving water quality model. In addition, it has been linked for pre- and post-processing in GIS and CAD systems (e.g. Liong et al., 1993, Karkowski and Walters, 1994, Wool et al., 1994). The Rain Block module reads specific meteorological data from the National Weather Service (NWS) and the Canadian Atmospheric Environmental Service and prepares the input blocks needed for SWMM. There are also "service" blocks, which provide post-processing procedures for tabular or graphical output for many constituents, and statistical analysis of model results.

The basic spatial unit for SWMM is the subcatchment, into which the modeled watershed is subdivided. Each subcatchment requires specification of an array of parameters characterizing its surface. Data requirements for hydrologic simulation include area, imperviousness, slope, roughness, width, depression storage, and infiltration parameters. Land use data is used to determine ground cover type for each model subarea. Depression storage can be estimated from rainfall and streamflow data, from modeling studies, or from literature. Soil infiltration factors can be spatially variable based on land use data and other soil type information. Infiltration is calculated using the Horton or Green-Ampt methods, at the user's choice. Manning's roughness values for pervious and impervious areas are estimated based on literature values for different ground covers. A version of Manning's equation is used to estimate flow rate from the subcatchment area based upon a conceptual model of the subcatchment as a "nonlinear reservoir," see Huber (1995). In addition, depending on what options are set for the loading calculations, additional parameters are necessary (e.g. build-up coefficients would be needed for the dry weather build up simulation). Additional data are necessary if the user intends to model snowmelt, subsurface drainage, and interflow.

The greatest strengths of SWMM are in its ability to model the details of urban hydraulic systems, such as drains, detention basins, sewers, and related flow controls. This requires input data on descriptions of weirs, orifices, pumps, etc., as well as drainage conduits and their network configurations. The EXTRAN block carries out a numerical solution of the complete St. Venant equations for the urban drainageways and conduits, by modeling the network as a link-node system (cf., DYNHYD).

Limitations of the model include lack of subsurface quality routing, no interaction of quality processes, limited kinetics (a first order decay rate can be specified for each pollutant in the Transport Block.), difficulty in simulation of wetlands quality processes, and a rudimentary scour-deposition routine in the Transport Block. There are options for constant concentration in runoff, input of a regression of load versus flow (i.e., a water-quality rating curve), specification of dry weather buildup and washoff, and the use of the Universal Soil Loss Equation. According to Computational Hydraulics, Inc, “The biggest impediment to [SWMM] usage is the user interface, with its lack of menus and graphical output. The model is still run in a batch mode (the user constructs an input file with an editor), unless a third party software is used for pre- and post-processing.”

Although model documentation attempts to provide guidance for all required inputs, SWMM has been described as “not user-friendly.” Depending on the simulation objective, input data requirements can be minimal to extensive. Data manipulation for input may take a significant amount of time. Obtaining sufficient data for calibration and validation is “highly recommended.” Without such data, SWMM “is at best only suited for relative comparisons between control strategies and should not be relied upon for prediction of absolute magnitudes of concentrations and loads” (Donigan et al., 1991; Huber, 1986). Codner (1991) compared the operational features of SWMM and HSPF, and found SWMM to be the more "user friendly" of the two, but commented on its difficulty of calibration because "of the number of degrees of freedom in the model."

Numerous applications of SWMM, especially to the urban environment, but occasionally to larger, mixed-land-use watersheds, have appeared in the literature over the quarter-century of the model's development. The USGS (Holmes and East, 1994) applied SWMM to basins in the Rolla, Missouri, area, apparently confining their modeling to runoff. They determined the dominant processes to be overland flow, interception storage, interception losses, evaporation, and infiltration. The model was calibrated, using observed data from four continuous rainfall gages and three continuous streamflow gages, for three runoff events, based on peak discharge, volume of runoff, and time to peak discharge from the beginning of simulation. Calibration accuracy was on the order of 10%.

Karkowski and Walters (1994) applied SWMM to the Winter Haven chain of lakes and its watershed to predict pollutant loading to the lakes and the impact of the loading on the lakes' water quality, linking SWMM to a GIS front-end, and to WASP as the receiving water model. SWMM produced a one-year simulation of daily flows and nutrient loading of nitrogen, phosphorus, and BOD to the lakes. These results were linked with WASP5 to simulate in-lake concentrations of ammonia, nitrate-nitrite, organic nitrogen, orthophosphate, organic phosphorus, BOD, dissolved oxygen and chlorophyll-a. Data from this one-year simulation was used to calibrate the model.

In Florida, the USGS did a comparative evaluation of five "models" for estimating peak discharges and runoff volumes, *viz*. the rational method, the USGS regional regression equations, the SCS (now Natural Resources Conservation Service) TR-20 model, the Army Corps of Engineers HEC-1 model, and SWMM. The results were reported in an Open-File report of limited distribution, which was not available to us in the time frame of the present project. According to the abstract of the study, sixty-six storms in 15 west-central Florida watersheds were modeled using these five methods. The watersheds ranged between fully developed urban and undeveloped natural watersheds, and all model runs were uncalibrated. The rational method was found to generally overestimate peak discharge (runoff volumes were not computed). The USGS regression equations are limited to storms of specific recurrence intervals, approximated by sixteen observed storms in the data base, for which the method overestimated both peak discharges and runoff volumes. No information on the performance of the other three models was given in the abstract.

Khan et al. (1997) calibrated and verified SWMM on Castro Valley, California, a 14.25 km^2 watershed with a long historical database. The watershed was subdivided into homogeneous hydrologic units, and the model was used to simulate both hydrological processes and pollutant accumulation, washoff, and decay. These authors report the match between the model and the data, on an annual basis, to be "remarkably close," with discrepancies less than 2.6 % for hydrology, 17% for TSS, 4.5% for copper, and 42% for lead. Sear and Bays (1991) used SWMM to estimate long term land surface runoff volumes to Lake Maggiore, a shallow 385-acre hyper-eutrophic lake located in St. Petersburg, Florida. A variety of urban land use types discharging untreated stormwater directly to the lake, as well as past dredging and filling, have been implicated in degrading lake water quality. While their emphasis was on hydrology, flow-averaged pollutant concentrations were used to estimate pollutant loads.

Tsihrintzis et al. (1995) and Tsihrintzis and Hamid (1998) used SWMM to simulate the quantity and quality of urban storm water runoff from four small (5-25 ha area) basins in South Florida, each with a specific predominant land use, viz. low-density residential, high-density residential, highway, and commercial. The database comprised 58 storm events each with rainfall hyetographs, runoff hydrographs and pollutant loadings for BOD, TSS, TKN and lead, which were used for calibration of the model. Pollutant accumulation used a power-law build-up dependent on the number of dry days. The impervious depression storage was generally found to be the most sensitive calibration parameter, followed by the Manning's roughness coefficients of conduit and overland flow, the Green-Ampt infiltration parameters and the pervious depression storage. Sixteen (16) independent rainfall events were used for verification of the model, which the authors judge a "good comparison with observed data for both hydrographs and pollutant loadings."

Barrett-McDaniels and Barrett (1997) coupled an EPA atmospheric transport and deposition model (ISCST3) into the build-up and wash-off blocks to evaluate the role of atmospheric deposition of the metals cadmium, chromium, copper, lead, and zinc on metal concentrations in the Elizabeth River, part of the Chesapeake Bay watershed.

The program is written in FORTRAN and is publicly available from the EPA. There is no charge for the software or example input and output files, but there may be a nominal fee (~$150) for full documentation manuals. The public domain version can be downloaded from:

ftp://ftp.epa.gov/epa_ceam/wwwhtml/swmm.htm

This includes the FORTRAN source code. Version 4.3 also includes a Windows interface. Continued development of the EPA version is underway by:

Dr. Wayne C. Huber
Department of Civil Engineering
Oregon State University
Corvallis, OR 97331-2302

A beta version of SWMM 4.31 is available, as is a beta version of SWMM 4.4 developed by Camp, Dresser & McKee, based upon modifications to Version 4.31. These may be downloaded from the OSU Internet site:

http://www.ccee.orst.edu/swmm/

There are several commercial proprietary versions, e.g. Thompson et al., (1993), providing a user-friendly I/O shell for SWMM. One example is PCSWMM'98, an impressive graphical design-and-display processing environment for Windows marketed by

Computational Hydraulics Int. (CHI)
36 Stuart Street, Guelph,
Ontario, Canada
N1E 4S5

who also offer a companion product PCSWMM GIS '98 that links to a variety of GIS software, including ArcView, see the corporate Internet site:

http://www.chi.on.ca/

Model: **SWRRB and SWRRB-WQ**

Source: Agricultural Research Service
U.S. Dept. of Agriculture
Grassland, Soil & Water Research Laboratory
808 East Blackland Road
Temple, TX 76502

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
lakes and reservoirs (SWRRB-WQ)
vadose zone

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no

flexible in its licensing requirements ☐ yes ☐ no

capable of transporting to variety of PC platforms ☑ yes ☐ no

source code available to potential users ☐ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☐ yes ☑ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

The Simulator for Water Resources in Rural Basins (SWRRB) was developed in the early 1980's for application to runoff and loadings from rural watersheds (Williams and Arnold, 1993). The model has been extensively documented (e.g., Arnold et al., 1990, Arnold and Williams, 1995) and widely applied (e.g., McIntosh et al., 1993, Srinivasan and Arnold, 1994). SWRRB was developed to apply to "ungauged rural basins" dominated by agricultural activities (Williams and Arnold, 1993). It is applicable to a range of catchments typical of Texas and evidences good comparison to data (e.g., Arnold and Allen, 1996, Bingner et al., 1997). Recently SWRRB has been extended and generalized into a newer product, SWAT. While SWRRB is still available (see below), SWAT is the preferred and recommended model for this family.

SWRRB evolved from earlier models at ARS, notably CREAMS, and in its development there was a subtle alteration in emphasis. The earlier models focused on management of agricultural crops as the objective, and the models were "field-scale," i.e. the spatial modeling unit was an area of homogeneous soils and vegetation. The processes of water application and usage, including infiltration, nutrient uptake and plant growth, and soil loss were depicted in the models with a range of cropping and tillage options. As a byproduct of this depiction, runoff from the field, and the sediment and nutrient concentrations in that runoff were determined. SWRRB focused on this runoff, thereby being developed as a loading model, although it preserved all of the original options for cropping and tillage.

In its original form, SWRRB was designed for application to a rather small watershed dominated by agricultural processes, with the emphasis on hydrology and sediment loading. With the inclusion of chemical constituents, notably nutrients and pesticides, it was re-designated SWRRBWQ (J. Arnold, BRC, pers. comm., 1999). For the purposes of this review, the two models are considered essentially equivalent.

The fundamental spatial unit for the model is the "subbasin" assumed to be homogeneous in all watershed parameters. The "basin" can be subdivided into up to 10 such subbasins. Each subbasin has an associated interior channel modeling the principal drainageway within that subbasin. In addition the outlet of each subbasin is conceived of being connected to the outlet of the basin by a routing channel. The terms "basin" and "subbasin" are relative, and the basin to which the model is designed to be applied is a small catchment with natural surface. The soils of each subbasin are subdivided into several layers extending from the surface throughout the root zone. The first (uppermost) soil layer of thickness 10 mm determines the disposition of water and controls sediment and chemical quality of the runoff water.

SWRRB is a "continuous" simulation model in the time domain, designed to perform long-term simulations in order to determine statistics of runoff and loadings. Thus, it includes storm events as well as the intervening nonstorm conditions in the watershed of plant growth, evapotranspiration, and desiccation. The timestep is 1 day.

The basic model components (Arnold and Williams, 1995) can be summarized as follows:

WEATHER

precipitation - user option of input of measured daily values or simulation based upon monthly probability distributions

air temperature - user option of input of measured daily values or simulation based upon monthly probability distributions

solar radiation - based upon statistics of radiation and correlation with precipitation and temperature

HYDROLOGY

surface runoff - determined by SCS Curve Number method

irrigation - specified by a water-stress trigger and requires input of ratio of volume assumed to run off the field

percolation - based upon a soil-layer water budget, vertical transport of water governed by hydraulic conductivity, field capacity and water in storage in each layer

lateral flow - downslope movement of water in soil layer

transmission losses - applied to channel routing, based upon effective hydraulic conductivity of channel sediments

potential evaporation - based upon air temperature and radiative budget, using user's choice of Priestly-Taylor or Hargreaves-Samani formulae (see Arnold and Williams, 1995)

soil water evaporation - computed from soil water content profile, and value of potential evaporation

pond and reservoir storage - a rudimentary water budget on a simple reservoir of fixed volume, to include cumulative effect of farm ponds or Section 566 reservoirs on water yield from a subbasin.

SEDIMENTATION

sediment yield - determined from Universal Soil Loss Equation (USLE), whose parameters must be specified for each subbasin

channel sedimentation - a gross sediment budget for the channel length with deposition based on Stokes settling and erosion based upon an adaptation of Bagnolds' power theory, see Williams (1980)

CROP GROWTH

soil temperature - function of soil layer depth, computed from air temperature, thermal conductivity governed by soil density and water content, and lagging factor for thermal inertia

leaf area index - computed from accumulated heat and plant biomass, and species-specific parameters

potential growth - estimated from incoming radiation and leaf area index

actual plant growth - based upon potential growth reduced by a factor determined by water and/or temperature stress for given species

plant transpiration (evaporation) - computed from potential evaporation and leaf area index of plant

NUTRIENTS

crop uptake of N & P - based on optimal (species-dependent) N & P concentration and fraction of total growth expressed in terms of heat accumulation

leaching - computed transport of N and soluble P out of soil layer by percolation and lateral flow

runoff - loss of nitrate and soluble P from uppermost soil layer based upon concentration and runoff flow

sediment loss of P - computed from partitioning coefficient, concentration of P in top soil layer and sediment yield

PESTICIDES

interception by plants - based upon loading rate and plant leaf area index

delivered to ground - surplus of pesticide application after loss to atmosphere and interception by plants

pesticide decay - first-order loss based upon input data of half-live for plant and soil

leaching - cascade calculation from top layer down, based upon percolation and initial pesticide concentrations in each layer

yield - computing from partitioning coefficient, sediment concentrations and runoff and lateral flow volumes

Input hydrological data for each subbasin includes area (as proportion of basin), the average interior main channel width, slope, length, Manning's n, and effective hydraulic conductivity (for transmission loss), runoff curve number, and fraction of each subbasin that flows into ponds or reservoirs, with specific volume and spillway data for each. Data on soils for each subbasin are also required, including number of layers, erosion factor, depth, density, water capacity, conductivity, clay content, maximum rooting depth, and particle size distribution. Most of the soil data for SWRRBWQ can be taken from the Soil Conservation Service (SCS) Soils-5 database. To specify crops and agricultural practices requires vegetation types, tillage operations, number of crops in rotation, planting and harvest dates, curve numbers, biomass conversion factor, water stress yield factor, harvest index, and if irrigation is an option, the date and the amount of irrigation, or the water stress and irrigation runoff ratio. The plant growth submodel follows the same philosophy as EPIC, but with considerable simplification, especially in the input data required. The pesticide chemistry is the same as used in GLEAMS.

SWRRB also has the capability to impose a receiving reservoir at the outlet of the basin. The model includes a rudimentary water and mass budget for this reservoir, based upon physical specifications and a simple operating rule.

Bingner et al. (1989) carried out a comparison of SWRRB, EPIC, CREAMS, ANSWERS and AGNPS using data from Mississippi research watersheds. They found SWRRB and CREAMS to produce results "close to" measured values more than the other models, and noted that SWRRB requires simpler inputs than CREAMS. SWRRBWQ has been less extensively validated than SWRRB. ARS reports that SWRRBWQ has been tested on 11 large watersheds from eight ARS locations throughout the United States (Arnold and Williams, 1987). McIntosh et al., (1993) employed SWRRB-WQ as well as EPIC and AGNPS to comparatively evaluate the effect of tillage and nutrient-management strategies on runoff.

The SWRRB model is no longer supported at USDA Blacklands Research Center, SWAT having essentially replaced SWRRB at USDA, and apparently can no longer be downloaded from the BRC Internet site. It can be obtained from the USDA Natural Resources Conservation Service Anonymous FTP server at:

ftp://ftp.nrcs.usda.gov/centers/itc/applications/wqmodels/swrrb/

but this is a convoluted process, since the model can only be obtained by self-extracting installations from floppy disks. So the floppy diskettes must be created by downloading and transferring the binary files to a diskette medium, then initiating the extraction procedure from the floppy drive. Both SWRRB and a relatively new Windows interface (General Sciences Corporation, 1993) are available from the EPA Internet site:

http://www.epa.gov/SWRRB_WINDOWS/index.html

Model: **TxBLEND**

Source: Environmental Section
Texas Water Development Board
S.F. Austin Bldg
Austin, TX 78711

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

estuaries
bays

Representative of Texas hydrological systems and Texas hydroclimates:

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☐ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☑ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☑ yes	☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 4 - Criteria specific to special-purpose estuary models

(1) Model formulation

spatial depiction: ☐ one-dimensional longitudinal ☑ two-dimensional horizontal
☐ two-dimensional longitudinal-vertical ☐ three-dimensional

variable geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☐ time varying tidal-mean
☑ fully time varying

accommodates riverine hydrographs? ☑ yes ☐ no

includes gravitational circulation (density variation)? ☐ yes ☑ no

basis for current distribution: ☐ direct input ☐ continuity only
☐ separate hydrodynamic model ☑ integral hydrodynamic model ☐ other

water quality (mass transport) capability included? ☐ yes ☑ no

sediment dynamics in estuary included? ☐ yes ☑ no

peripheral sediment loads included? ☐ yes ☑ no

(2) Numerical solution

method for numerical specification of estuary geometry:
☐ manual input ☐ import of standard files ☑ grid generator ☐ GIS

numerical solution method (spatial)
☐ finite-difference ☑ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

Source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

Minimum hardware requirements of model:

☐ PC compatible ☑ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

Has the model been routinely flanged with a watershed model? ☐ yes ☑ no

Does model coding/input allow easy modification of parameters, constants and input files to better represent Texas systems? ☐ yes ☑ no

(4) Suitability for Texas estuarine systems.

Demonstrated application to bays or estuaries typical of Texas? ☑ yes ☐ no

Acceptable performance in model validation studies? ☑ yes ☐ no

Acceptable level of technical acceptance? ☐ yes ☑ no

(5) Capability for implementation in a GIS environment.

Has model been operated with GIS derived inputs, either with or without an associated watershed model? ☐ yes ☑ no

Has model output been displayed using modern visualization capabilities? ☑ yes ☐ no

Discussion

TxBLEND evolved from a finite-element program developed by Gray and Lynch in the 1970's (see Lynch and Gray, 1979, Gray, 1987) for application to tidally dominated circulations of shallow coastal embayments. For the past two decades, the TWDB has invested a considerable effort in the expansion and validation of TxBLEND for application to the Texas bays. The primary objective of the modeling work has been the capability for salinity prediction, a parameter judged to be central in evaluating the effect of freshwater inflows on the ecology and productivity of these bays. The formulation and operation of the model is summarized in the draft user's manual (Matsumoto, 1999).

Briefly, the model is a numerical solution to both a hydrodynamic and a mass-transport equation, the latter being specifically applied to salinity. These equations are integrated in the vertical so the vertical dimension is eliminated, and the model calculations are for the two-dimensional circulation. While the original Gray-Lynch model focused on tidally dominated environments, the TWDB has incorporated horizontal salinity gradients into the hydrodynamics and coupled the mass-balance solution for salinity. Numerical integration is effected by the method of finite elements, using a tiling of triangular elements.

The model is fully dynamic. It includes several options for numerical time-stepping, and for relative weights of terms, especially the nonlinear field acceleration and nonlinear advective transport terms. Matsumoto (1999) notes that, although the fully implicit timestep (one of the options of TxBLEND) is theoretically unconditionally stable, TxBLEND in fact exhibits numerical instability if the time step is taken to be too large.

The model equations also include dispersion coefficients, additional diffusive-type viscosities (to control nonlinear instability) and an empirical parameter "bigG," which—though stated (Matsumoto, 1999) to originate in a method to enforce conservation in the numerical form of the continuity equation, see Kolar et al. (1992)—is in effect a calibration parameter whose value must be specified for every computational node in the model domain. Moreover, different inflow regimes require different Big G arrays.

In many respects, TXBLEND is an attractive alternative for TMDL modeling where this would be necessitated in a Texas Bay. It has been designed for specific application to the Texas systems, and finite-element input grids are already available for each of the Texas estuarine systems, except for the Laguna Madre. The vertical-mean geometry, i.e., two-dimensional horizontal, is suitable for most water-quality distribution issues in the Texas bays, because of the extreme shallowness of these systems and the lack of significant vertical gradients in concentration. TXBLEND would be especially appropriate for TMDL problems in which tidal action is the predominant hydrodynamic control, since this is the type of dynamics for which the model is eminently suited.

On the other hand, in its present form, TXBLEND does not include a water-quality module. It does have a mass-transport capability, but this is limited at present to salinity. No kinetics specific to traditional water-quality parameters have been incorporated into the model. There is no capability for wasteload injection, either point or nonpoint. Perhaps the best use that could be made of TXBLEND in the TMDL process is to output the current field into a suitable mass transport and kinetics model such as WASP.

The model is coded in FORTRAN, but the program is complex and its modification should not be undertaken by an inexperienced modeler. The model is computationally intensive, and originally required a dedicated mini-computer work station, but as PC computing resources have advanced, the model can now be accommodated on a high-end PC platform. Although the program has been developed with public monies, it has had very limited distribution outside the TWDB. It cannot be freely downloaded but must be requested from the Bays and Estuaries Program of TWDB. To help defray costs of model copying and to respond to inquiries about set-up and operation, the user is charged a fee, which is variable but thus far has been on the order of several thousand dollars.

Model: **WAM (Watershed Assessment Model)**

Source: Soil and Water Engineering Technology, Inc.
3448 NW 12th Ave.
Gainesville, FL 32605

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds
streams and rivers

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☑ yes	☐ no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☑ yes	☐ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☐ yes	☑ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☑ no
source code available to potential users	☐ yes	☑ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

WAM is a GIS-based interactive watershed model marketed by SWET of Gainesville. The model has been evolving for about a decade, one of its earlier incarnations being the Basin New Zealand (BNZ) model (Cooper and Bottcher, 1993; Bottcher et al., 1998). It is a grid-based distributive model that in its present version uses GLEAMS source loads. There are two versions: WAM-A routes flow and waterborne constituents to the outlet of the basin using "a GIS algorithm", and WAM-D uses a stream routing model. Grid cells are 1-ha squares, which are organized into sub-basins, i.e. individual watershed subdivisions of the "primary" basin.

The model is based upon ARC/INFO modules, and uses ARC/INFO heavily to compute distances between features, distances to streams, subareas and to manipulate raster data files of soils, topography, land use and related data bases. In WAM-A, constituents are subjected to attenuation according to the flow-path travel time to a stream or outlet, a simple first-order decay. Only limited publication is available of the formulation of the model (see reference list), but there appears to be a great deal of empiricism in the basic model formulation, and that most of the developmental effort has been invested in the organization and visualization of model output.

No information is available about the source code. The limited information available from SWET indicates that WAM operates on UNIX platforms. A demonstration file can be downloaded from the SWEP Internet website:

http://www.swet.com/

Model: **WASH123D**
(WAterSHed systems of 1D stream-river network, 2D overland regime, and 3D subsurface media)

Source: Waterways Experiment Station
U.S. Army Corps of Engineers
Vicksburg, Mississippi

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Watersheds
Rivers and streams
Groundwater: vadose zone and aquifers

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☐ yes	☑ no
basins dominated by fluvial drainageways	☑ yes	☐ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☐ yes	☑ no
in public domain	☐ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no

capable of transporting to variety of PC platforms	☐ yes	☑ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application	☐ yes	☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency	☑ yes	☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic	☑ yes	☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

This is a combined watershed/river-drainage/groundwater model whose development is underway by G-T Yeh, H-P Cheng, and J-R Cheng, of Penn State University, under sponsorship of the USCE Waterways Experiment Station. It is supposed to incorporate the most advanced combination of surface hydraulics and infiltration models with state-of-the-art numerical integration and visual displays.

The development of the model is not as far along as informal discussions suggested and in fact is still very much in the stage of testing numerical formulations. No practical applications have yet been made, and the program appears, from the results in Yeh et al. (1998), to be a long way from having complete water quality capability, or from being in a "user friendly" operational format.

Model: **WASP (Water-quality Analysis Simulation Program)**

Source: Environmental Protection Agency
Center for Exposure Assessment Modeling
960 College Station Road
Athens, GA 30605-2700

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

Streams and Rivers
Lakes and Reservoirs
Estuaries and Coastal Waters

Representative of Texas hydrological systems and Texas hydroclimates:

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☑ yes	☐ no
streams dominated by fluvial-type bathymetry	☑ yes	☐ no

Lake and reservoir models, capabilities:

run-of-the-river reservoirs	☑ yes	☐ no
relatively shallow lakes	☑ yes	☐ no
seasonal temperatures fall below that of maximum density	☑ yes	☐ no

Estuary models, capabilities

lagoonal estuaries	☑ yes	☐ no
channel estuaries	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution ☑ yes ☐ no

in public domain ☑ yes ☐ no

flexible in its licensing requirements ☑ yes ☐ no

capable of transporting to variety of PC platforms ☑ yes ☐ no

source code available to potential users ☑ yes ☐ no

(3) Model program lineage.

Sufficient history of application ☑ yes ☐ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☐ **eliminate** ☑ **consider**

Screening Level 2 Criteria for stream/river models

(1) Model formulation

variable channel geometry? ☑ yes ☐ no

variable bed characteristics? ☑ yes ☐ no

time integration: ☐ steady-state only ☑ time varying

accommodates flood-type hydrograph? ☑ yes ☐ no

basis for current computation: ☑ direct input ☐ continuity only ☐ kinematic wave ☐ complete hydraulic model ☐ other water quality (mass transport) capability included? ☑ yes ☐ no

sediment dynamics in stream included? ☑ yes ☐ no

peripheral sediment loads included? ☑ yes ☐ no

capability to include channel estuaries or run-of-river reservoirs? ☑ yes ☐ no

(2) Numerical solution

method for numerical specification of stream channel and network:
☑ manual input ☐ import of standard files ☐ GIS

numerical solution method (spatial)
☑ finite-difference ☐ finite element ☐ boundary element ☐ other

(3) Implementation for computer operation

properties of source code:

☑ FORTRAN ☐ C ☐ Visual BASIC ☐ other

hardware requirements of model:

☑ PC compatible ☐ workstation or high-end PC ☐ Macintosh
☐ Supercomputer (e.g., Cray) ☐ other ☐ unknown

has the model been routinely flanged with a watershed model? ☑ yes ☐ no

Level-2 Screening: ☐ **eliminate** ☑ **consider**

Discussion

WASP is distributed by the EPA Center for Exposure Assessment Modeling of the Environmental Protection Agency. This fifth generation model, currently designated WASP5, evolved from the estuary DO model of Robert Thomann (1963) of the early 1960's. The model was extended in the 1970's to include other water quality parameters, notably those involved in algal productivity, see Thomann et al. (1970) and Thomann (1975). The model was extensively recoded in the early 1980's (Di Toro et al., 1981) and has undergone considerable debugging and updating since, including adaptation to the PC environment.

The basic philosophy of the model is to provide a general numerical solution scheme in 1 to 3 dimensions for transport and reaction kinetics, with capabilities for some very general and complex multiparameter kinetic interactions. The currents and diffusivities that quantify advective and dispersive transport are not part of the model, but are to be imported from another, special-purpose model. Because these hydrodynamic elements are external to the model, the model is in principle applicable to rivers, lakes and estuaries, in one or more spatial dimensions. The authors of WASP developed the model with customization in mind. The code is divided into various subprograms, with the kinetics subprogram (WASPB) accessible to easy modification. Additional parameters, constants, and state variables can be added, once a good understanding of the model structure is gained. The kinetics can also be modified to included additional (or coupled) reactions.

The current program consists of three major subprograms:

DYNHYD5 - a link-node hydrodynamic model that simulates water flow, including, if necessary, tides and wind.

TOXI5 - simulates dissolved and sorbed chemical concentrations in the bed and overlying waters; kinetic structure adapted from EXAMS2

EUTRO5 - simulates nutrients (DO and phytoplankton dynamics) in the water column and sediment.

The type of modeling desired controls the kinetic subroutine chosen (i.e. TOXI or EUTRO). Each of the three subprograms of WASP can be operated as a stand-alone program.

The hydrodynamics for WASP can be defined in three different ways:

(1) the user can define steady state flows and bulk dispersion coefficients within the input file

(2) output from DYNHYD (WASP's hydrodynamic subprogram) can be used
(3) an outside hydrodynamic model can be linked to the WASP transport submodels (TOXI and EUTRO)

Although DYNHYD is set up to link easily to the WASP transport program, other hydrodynamic models can be run and the output can be formatted for input to WASP. In addition, steady state flows can be set directly within the WASP transport model (provided these can be legitimately estimated), which circumvents the use of any hydrodynamic model.

Transport or transport-related mechanisms included in WASP are: advection and dispersion in the water column, advection and dispersion in the pore water, settling, resuspension, and sedimentation of up to three solid classes; and evaporation and precipitation. Information about proportion of flow and dispersion coefficients needs to be specified for each transport field. In addition, for each state variable being modeled the user must indicate boundary conditions, initial conditions, constants and parameters.

WASP solves the equations of conservation of mass by a finite-difference method, utilizing rectangular coordinates. That is, WASP5 depicts the watercourse as a network of rectangular-box segments that exchange mass (water and constituent) at the segment boundaries. A channel, lake, or bay can be either or both vertically and horizontally segmented. The underlying sediment is also divided into boxes (segments) and assigned parameters to quantify sediment characteristics (i.e. bulk density). Because the boxes are rectangular (expressed as volumes with cross-sectional areas), channel or shore side slopes are not accounted for in this model. The segment grid is developed manually by the user – and may be somewhat difficult to automate, depending on the system. WASP has the advantage compared to other complex spatial models that the level of complexity of the grid generation is easily defined by the user. Therefore, a system can be represented by a relatively simple model grid. The inputs necessary to define the grid are segment volumes, cross-sectional areas, segment type (upper or lower benthic and epilimnion or hypolimnion water), and exchange segments (i.e. segment above, segment below, downstream segment, and upstream segment).

For constituents bound to or associated with sediments, the constituent may migrate downward or upward in both the solid (settling and resuspension) and dissolved (pore water diffusion) phase. Sorption is modeled through both TOXI and EUTRO by supplying partition coefficients (which can be spatially variable) for each constituent. Sediment modeling *per se* is described below.

Other parameters necessary for the TOXI subprogram depend on which transformation processes are important for the constituents of interest. These processes can include first and second order decay coefficients, reaction rate coefficients (including parent-daughter reactions), light extinction parameters, water temperature, DOC content, fraction organic carbon content, pH, oxidant concentration, bacterial concentration, wind velocity, air temperature, and chlorophyll-a concentration. In addition, the model requires the molecular weight of the constituent (for certain reaction forms) and temperature functions if there is a temperature control for seasonal or diurnal effects on pollutant behavior. Obviously, TOXI has the potential to become quite complicated and data intensive – however, simple systems can be successfully modeled by avoiding complex parameterization.

In EUTRO, boundary conditions, initial concentrations, and loads are specified by the user. As with TOXI, EUTRO has the potential to be a complex, data-intensive model - up to 16 spatially variable environmental parameters (e.g. water temperature, reaeration rate, and sediment oxygen demand) and 60 rate constants (e.g. oxygen-carbon ratio, denitrification rate and phytoplankton N-C ratio) may be specified as needed. A number of constants need to be supplied for both the water column and bed segments and many of these can be determined from the chemical/ environmental database provided with WASP. Like TOXI, temperature dependencies on different parameters and constants can be included.

WASP models sediment transport through three of its "transport fields" (settling, resuspension, and sedimentation). Sediment is simulated using the TOXI subprogram and can incorporate total solids as one variable, or can represent up to three solids types (e.g. sand, silt, clay, organic solids, or inorganic solids). The concept behind the modeling of sediment is a simple mass balance on each solids variable performed in each segment. The mass balance, applied to both bed and water column segments, is based on advection and dispersion rates, as well as settling, deposition, erosion, burial, and bed load rates. Each type is defined by specifying its settling and erosion rates and its organic content. All solids transport rates can be varied in space and time by the user. There are, however, no special process descriptions for solids transport. Erosion rates, for example, are not programmed as a function of sediment shear strength and water column shear stress, as is commonly the case. Consequently, the TOXI5 sediment model should be considered descriptive, not predictive, and must be calibrated to site data.

The parameters necessary for sediment simulation (Ambrose, *et al.* 1993) are the following:

- Bed Volume Option-- The user must determine whether bed volumes are to be held constant or allowed to vary.
- Bed Time Step-- While mass transport calculations are repeated every model time step, certain benthic calculations are repeated only at this benthic time step, in days.
- Sediment Transport Velocities, m/sec-- Time variable settling, deposition, scour, and sedimentation velocities can be specified for each type of solid.
- Cross-Sectional Areas, m^2-- The interfacial surface area must be specified for adjoining segments where sediment transport occurs. These surface areas are multiplied internally by sediment transport velocities to obtain sediment transport flows.
- Boundary Concentrations, mg/L-- At each segment boundary, time variable concentrations must be specified for total solids, or for each solids type simulated. A boundary segment is characterized by water exchanges from outside the network, including tributary inflows, downstream outflows, and open water dispersive exchanges.
- Waste Loads, kg/day-- For each point source discharge, time variable sediment loads can be specified for total solids, or for each solids type simulated. These loads can represent municipal and industrial wastewater discharges, or urban and agricultural runoff.
- Solids Transport Field-- The transport field associated with total solids or each solids type must be specified under initial conditions.
- Solid Density, g/cm^3-- The average density of the total sediment, or the density of each solids type must be specified.

- Initial Concentrations, mg/L-- Concentrations of total sediment or of each solids type in each segment must be specified for the time at which the simulation begins.
- Dissolved Fraction-- Set to 0.

The data needs of WASP are not overwhelming, as models of this complexity go, but information about the system concerning initial conditions and boundary conditions is essential. The fourth release (WASP4) incorporated the ability to input non-point (or diffuse) source loadings. WASP is capable of handling time-varying problems, but this requires time-varying flow and loading inputs, in addition to time varying parameters and temperature dependencies. Also, the companion hydrodynamic model DYNHYD may exhibit problems with fully dynamic events such as storm hydrographs. The time breaks in WASP for time varying inputs can be few or many. A time varying input can be viewed as a step function or can be integrated between breaks. The input is defined by the length of the time break and the total number of time breaks - the user can outline a varying number of lengths. The value of the break and the number of breaks the value is valid are then defined within the input file. The only limitation to the input file would be the amount of space available on the computer's hard drive to store large text files WASP has been applied on numerous projects through the world and storm events have been successfully simulated using the program.

WASP the potential to be an extremely complex modeling system – as the complexity increases, the number of parameters and constants needed for the run increases. In many systems, a high level of complexity is probably not necessary to obtain sufficiently accurate results. It is not, however, a "turn-key" model, but must have a significant amount of external input, most notably the hydrodynamic environment. This same structure, however, facilitates flanging WASP with other models.

WASP has been used for about twenty years and is a well-established water quality model, supported by the USEPA. Its current version (WASP5) has been in use since the mid-nineties and has been applied in Texas, as well as many other states and countries. Examples of modeling projects that used WASP (version 4 or 5) have included DO/BOD studies in the Houston Ship Channel (Benaman, 1996), the modeling of non-point source nutrients in the

Milwaukee River (Hajda and Novotny, 1996), and a USEPA TMDL Case Study in Delaware (Morton, 1993). Phosphorous dynamics were simulated in the Carson River of Nevada (Warwick et al., 1997) and in a wetland of Ontario (Lopezivich, 1996). Pickett (1994, 1997) used WASP5 to address the low DO problems of the Black River, a tributary of the Chehalis River in western Washington State. WASP has been applied to modeling toxics and organics (e.g., Vuksanovic, et al., 1996 and Hosseinipour, 1993). Zhou (1998) described a WASP application to a combined stream-reservoir system, to evaluate impacts of biosolids application to agricultural lands in the watershed. The simulation included proposed biosolids procedures, reservoir operating rules, and relative geography of the application lands, and determined that a series of small floods were more significant in total loading than a large flood.

As part of a TMDL study, field data were collected during two summer dry seasons and WASP5 was used to assess the effects of BOD, ammonia, and nutrient loads. Hernandez et al. (1997) used WASP5, normally employed for seasonal eutrophication evaluation, to determine daily phytoplankton and nutrient dynamics in perturbed microcosms. In particular, EUTRO5, was calibrated for a "well-behaved" microcosm, then applied to other microcosm experiments. Jin et al. (1998) used WASP/EUTRO to assess eutrophication in Lake Okeechobee.

The Peconic Estuary, Long Island, N.Y., has suffered from repeated brown tide outbreaks, one particularly intense episode occurring in 1985-86. Morton et al. (1989) applied DYNHYD4, WASP4 and EUTRO4 to the system, simulating CBOD, nutrients, chlorophyll, salinity and oxygen, using data from 1976 for calibration. An intensive data compilation and collection program has been instituted, including an assessment of point and nonpoint source pollutant loadings. This information was used in a WASP5 application (Minei and Dawydiak, 1995), in which the most significant (controllable) load was found to be the Peconic River and the Riverhead Sewage Treatment Plant due both to their magnitude and their location in a poorly-flushed area of the system.

WASP has also been used internationally in Belgium for modeling PCBs (Vuksanovic, et al., 1995) and simulating nutrients and synthetic organics in a Russian River (Hosseinipour, 1993). Suarez et al. (1995) developed a short-term dynamic model of the Nalon River in Spain, using an older application of QUAL2E, which had been calibrated and verified based upon field data. WASP5 was applied to the dynamic problem, addressing the daily fluctuations in water quality and the impact combined sewer overflow (CSO) has on the upper stretch of the river Nalon. All field study data and kinetic constants and parameters from QUAL2E were used for the dynamic model, and good calibration and verification were accomplished with WASP5. The simulations included daily variation of DO, BOD, ammonia, organic nitrogen, nitrates and total nitrogen. Koh et al. (1993, 1995) studied dissolved oxygen in a tidal reach of the Johor River, Malaysia, which is impacted by agro-industrial waste. DYNHYD5 was used to model tidal hydrodynamics, and WASP5 to assess the distributions of dissolved oxygen.

De Smedt et al. (1997) report an application to studying heavy metals in the Scheldt estuary, which required consideration of tidal hydrodynamics, sediment transport, and sorption of heavy metals on suspended matter. Five heavy metals were modeled under average conditions, with a feed-forward model: hydrodynamics, salinity, suspended sediment, heavy-metals transport. They report good agreement of modeled concentrations with observations of sorbed heavy metals, suspended sediment and salinity in the estuary, indicating accumulation of heavy metals in the zone of the turbidity maximum.

An advantage of WASP in many modeling strategies is its ability to link to other models through input and output formatting. Although DYNHYD5 is set up to be read directly into WASP, it is fairly easy to use different hydrodynamic models and format their output for input to WASP. Because the source code is readily available, it is not difficult to modify the way in which WASP reads input and produces the output, which facilitates coupling with other models and programs. Watershed models, in particular, have been successfully linked to WASP, including SWMM and AGNPS. WASP has been linked to SWMM directly through file I/O (Karkowski and Walters, 1994) and through a program called Linked Watershed/ Waterbody Model (Computational Hydraulics Int., 1999). Kao et al. (1998) integrated AGNPS and WASP to evaluate the effects of nonpoint runoff on quality of a small off-stream reservoir.

GIS and WASP links have been accomplished on a number of levels. An early integration is reported by Dilks and Slawecki (1990), who developed two types of GIS/water quality model linkages: "partial linkage" of PC ARC/INFO to WASP4; and "complete integration" using customized software. The former addresses only the links where an immediate benefit is gained, *viz*. assistance in preparation of model inputs and graphic display of model results. The latter resulted in the development of an "Interactive Modeling Framework," a user-friendly model interface for performing water quality simulations. These workers commented that "the primary limitation of complete integration is that the majority of the computer capabilities required do not naturally reside in the GIS environment."

Karkowski and Walters (1994) report development of a GIS-SWMM-WASP linked model, which was applied to the Winter Haven chain of lakes and its watershed. GIS files of land use and soil types were input to a preprocessor for creating a SWMM file, which was also driven with hourly rainfall for one year to produce daily flows and nutrient loading of nitrogen, phosphorus, and BOD to the lakes. These loads were linked to WASP5 to simulate in-lake concentrations of ammonia, nitrate-nitrite, organic nitrogen, orthophosphate, organic phosphorus, BOD, dissolved oxygen and chlorophyll-a.

DePinto *et al.,* (1994) developed a connection between WASP4 and ArcInfo using the Arc-Macro Language for water quality/watershed modeling. They call the integrated watershed-GIS system GEO-WAMS (Geographically Based Watershed Analysis and Modeling System). There are five components: a GIS-based data management system, a watershed model, a data-model management interface, an "analyst support toolkit", and an interactive user interface. WASP4 is coupled into the system for simulation of dissolved oxygen in a receiving water body. A loose connection between WASP5 and ArcView 2.1 using Avenue and FORTRAN was developed by Benaman (1996). Additional research is being conducted on the connectivity of WASP with GIS (Simachaya, pers. comm., 1998).

WASP5 is written in FORTRAN, and model executables and documentation may be downloaded from the EPA Internet site:

http://ftp.epa.gov/epa_ceam/wwwhtml/wasp.htm

Minimum requirements to run WASP are a 286 PC with a math coprocessor, 640 kB of RAM, and 5 MB hard drive space. These specifications are minimum and for most simulations, a faster machine with more memory would be recommended.

Although loose linkages to WASP5 for GIS have been accomplished, as noted above, one of the stumbling blocks in the newest version of the model is the introduction of WISP. WISP is a DOS-based user interface that is meant to assist the user in developing input files and running the model. However, the some of the coding which runs WISP is integrated into the WASP5 code. This presents a problem if the desire is to integrate WASP somewhat seamlessly into GIS. An example of this problem was illustrated in the ArcView/WASP5 connection developed at the University of Texas (Benaman, 1996). Although WISP was never executed during an analysis in ArcView, when the model was running, a graphical screen appeared displaying the results of the model at each time-step. Although informational, this display used computer memory and actually slowed down the model run-time considerably. Attempts to disable or delete this graphical display were not successful due to its integration into the WASP code.

Model: **WEPP (Water Erosion Prediction Project)**

Source: National Soil Erosion Laboratory
USDA-ARS
1196 SOIL Building
Purdue University
West Lafayette IN 47907-1196

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds (farm-scale catchment)
vadose zone (upper soil horizons)

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☑ yes	☐ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☑ yes	☐ no
in public domain	☑ yes	☐ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☐ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

Sufficient history of application ☐ yes ☑ no

(at least five years in more-or-less current form of application to watercourse of relevance to Texas)

Sufficient currency ☑ yes ☐ no

(most recent application within the past ten years)

(4) Model conceptual philosophy

Deterministic ☑ yes ☐ no

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

The prediction of sediment erosion and loss from a small watershed based upon rainfall and soil properties is one of the basic goals of all of the models designed for application to agricultural watersheds. The physics of this process is, however, complex, and in most cases is avoided by treating key processes with statistical models derived from field data. The Universal Soil Loss Equation (Wischmeier and Smith, 1978), common to many of these models, is a statistical model. WEPP is a recent model constructed to better depict the erosion process by relations closer to the basic physics.

In its conceptual formulation, WEPP is closely related to CREAMS, SWRRB and EPIC, and, in fact, uses program elements or functional relations from each of these in various places in the model. The differences appear to be that WEPP strives for more "process-based" formulations, rather than statistical relations, and is programmed specifically for the PC environment, in contrast to being adapted from mainframe codes.

The primary components of WEPP are hillslopes, channels, and impoundments. WEPP is designed for application to a field-scale catchment or small watershed. Geometrically, only one such watershed can be modeled, but it can be composed of a network of hillslopes and channels. The hillslope and channel components are further divided into hydrology and erosion components. The water balance includes evapotranspiration, soil water percolation, canopy rainfall interception, and surface depressional storage. The original coding of WEPP (1989) was described as having three "versions", i.e. three configurations to which the model applies: profile, watershed and grid (Laflen et al., 1991). The profile version (now the "hillslope" version) employed the Revised USLE in its rill-interrill erosion submodel. In the other "versions" of WEPP, the RUSLE is replaced with deterministic equations, based on infiltration theory, soil physics and erosion mechanics (Lane and Nearing, 1989).

Channel infiltration is calculated by a Green-Ampt Mein-Larson infiltration equation. The Penman equation is used for evaporation, and transpiration is computed in terms of a potential soil evaporation. Flow depth and hydraulic shear stress along the channel are modeled by regression equations based on a numerical solution of the steady state spatially varied flow equations (Ascough et al., 1997). Detachment, transport, and deposition within constructed channels or concentrated flow gullies are calculated by a steady state solution to the sediment continuity equation. The impoundment component routes runoff and sediment through several types of impoundment structures, including farm ponds, culverts, filter fences, and check dams. Ascough et al. (1997) provide an overview of the conceptual basis and model formulation, including mathematical representations of the processes simulated by the channel hydrology and erosion components.

WEPP includes a simulation of plant growth and decomposition, which supplies basic parameters for computing transpiration from vegetation. The infiltration model is based upon DRAINMOD (Skaggs, 1978). The model is strongly based upon agricultural row-crop watersheds with tile or ditch drainage. A key parameter in the surface drainage model is depressional storage, which is modeled by a stochastic roughness, see Savabi (1993).

WEPP has received relatively little application outside the staff of the National Soil Erosion Research Laboratory, which is responsible for development of the model, and its application history is almost entirely in agricultural systems. (A bibliography of WEPP-related publications with over 170 citations is available for download from the WEPP Internet site, see below. Most of these are "gray-literature" or "conference" publications by members of the development team, or are literature references upon which elements of WEPP have been based.)

Williams and Nicks (1993) compared prediction of the effects of vegetative filter strips using WEPP and CREAMS, a purely comparative exercise. Reyes and Cecil (1997) evaluated surface runoff volume predictions of GLEAMS, EPIC and WEPP; and the soil loss predictions of GLEAMS, RUSLE, EPIC and WEPP including comparison with observed data from experimental plots located near Greensboro, North Carolina, using conventional tillage, strip tillage, no till controlled traffic, and no till full traffic. They found that while EPIC and WEPP satisfactorily predicted runoff, none of these models satisfactorily predicted soil loss. Yoon et al. (1997) similarly compared three models, GLEAMS, EPIC and WEPP, to a field-sized watershed in the Tennessee valley region of Alabama, with two tillage systems, three years of conventional tillage followed by three years of conservation tillage of cotton. Model comparisons considered both runoff and losses of sediment, as well as losses of N and P. They found that GLEAMS and EPIC underpredicted NO_3 losses in runoff for both tillage systems. EPIC simulated tillage effects on soluble-P losses better than GLEAMS but poorly predicted annual organic-N and P losses in sediment, mainly due to overpredicted sediment losses. The GLEAMS prediction of annual organic-N and P losses in sediment was more acceptable than that of EPIC. WEPP apparently performed best of the three, with predicted sediment losses close to observed data for both tillage systems.

The current version of the model is available through the WEPP Internet site:

http://topsoil.nserl.purdue.edu/weppmain/wepp.html

The source code is written in FORTRAN but is not available to nonparticipants in the WEPP project. In recent years, WEPP has been extensively revised with a modern PC interface, and could be properly regarded as a "family" of models including both lumped and distributed process- modeling capabilities. A Windows interface for WEPP is in development, and the beta version may be downloaded from the above site. A tutorial with additional information about the model is located at:

http://wepp.www.ecn.purdue.edu/~wepphtml/wepp/wepptut/jhtml/intro.html

The limitations of WEPP for application to Texas TMDL are its narrow range of application to small agricultural watershed, and the "in-development" status of the program. A perusal of the FAQ's on the WEPP Internet site clearly demonstrates that both the operational aspects of the program and the technical algorithms for process computation are very much subject to bugs which are still being discovered and corrected. Because of its mechanistic conception, WEPP may eventually evolve into a model with TMDL capabilities, and its development should be monitored.

Model: **WMS (Watershed Modeling System)**

Source: Scientific Software Group
P.O. Box 23041
Washington, DC

Screening Level 1 Criteria

(1) Stated physical system(s) for which model is applicable.

watersheds

Representative of Texas hydrological systems and Texas hydroclimates:

Watershed models, capabilities:

low-relief terrain, semi-arid to subhumid basins	☐ yes	☑ no
basins dominated by fluvial drainageways	☐ yes	☑ no
substantially altered hydrology due to storage and conveyance systems	☐ yes	☑ no
substantially altered hydrology due to urbanization	☐ yes	☑ no

Stream and river models, capabilities:

flashy and low-baseflow rivers and tributaries	☐ yes	☑ no
streams dominated by fluvial-type bathymetry (rectangular segments only)	☑ yes	☐ no

(2) Existence of model as operating computer program for general applicability.

model code:

capable of copying and distribution	☐ yes	☑ no
in public domain	☐ yes	☑ no
flexible in its licensing requirements	☐ yes	☐ no
capable of transporting to variety of PC platforms	☑ yes	☐ no
source code available to potential users	☐ yes	☐ no

(3) Model program lineage.

[not applicable]

(4) Model conceptual philosophy

[not applicable]

Level-1 Screening: ☑ **eliminate** ☐ **consider**

Discussion

WMS is not a model so much as it is a convenient interface to standard models, including HEC-1, TR-20, NFF, and the Rational Method. It is also proprietary. For these reasons, it was given no further consideration in this review.

Information about this "model" may be found at the Internet website:

http://www.scisoftware.com/products/wms_overview/wms_overview.html

4. CONCLUSIONS AND RECOMMENDATIONS

Surface watercourses of Texas fall into a range of categories. Following the hydrological cycle, these proceed from small natural, urban or agricultural catchments, to basin-scale watersheds, through small evanescent streams to major perennial rivers, from small uncontrolled lakes to multi-purpose run-of-the-river reservoirs, and finally to the tidal and salt-intrusion reaches of the principal rivers, and the coastal embayments into which these rivers debouch. For many of these watercourses, there is significant interaction with the subsurface components of the hydrological cycle: the surficial soils, the root zone, vadose zone and aquifers. In principle, these are all manifestations of the flow of water so are equally amenable to treatment by the principles of fluid dynamics. A naive view might be that there should therefore be a single model equally applicable to all of these watercourses, for each of which the user merely alters the spatial geometry. In fact, the controlling processes, the nature of the hydraulic responses, and the parameterizations of the hydrodynamic and kinetic terms are so variable among these watercourses that the only viable strategy is to develop special-purpose models appropriate for specific types of watercourses. This is indeed the strategy that has been pursued in the development of the various models reviewed in this study.

In selecting a model for application to a TMDL, the first requirement is to clearly define the nature of the water quality problem addressed. This includes specification of:

- probable source of contaminants (e.g., landscape practices or environments, point source discharges, interaction with natural sources, production by kinetic reactions, etc.)
- categories of watercourse(s) involved,
- time scale of contamination (steady discharge, flashy loads due to storms, reaction rates)
- time-space manifestation of degraded water quality (high detention, low dilution, extremes of temperature)
- interaction among parameters (co-reacting constituents, particulate sorption)
- time-scale of response in watercourse (steady-state or equilibrium concentration, asymptotic variation, rises or spikes of high concentrations, etc.)

- spatially variability in water quality response (vertical stratification, zones of toxicity or arrested biological activity, nuisance algae formation), hence the spatial dimensionality necessary in the analysis of water quality

These together dictate the capabilities required of the model or models to be employed.

The categories of watercourses that we anticipate to represent the bulk of TMDL projects in Texas are:

(1) streams and rivers, in which the longitudinal variation of water quality is of concern
(2) run-of-the-river reservoirs that exhibit little to limited vertical stratification
(3) larger, deep reservoirs which exhibit seasonal stratification
(4) reservoirs of either type with substantial internal circulation due to power-plant operations
(5) tidal and/or saline intrusion reaches of rivers, in which the longitudinal variation of water quality is of concern
(6) deeper tidal systems, primarily navigation channels, affected by tides and salt intrusion, in which both longitudinal and vertical variations of water-quality parameters are important

We note that TMDL problems may be encountered on other types of watercourses, such as the open, shallow bays of the coast, the small-scale or "mixing zone" regions of rivers, lakes and estuaries, or the nearshore coastal environment, but we expect relatively few such situations to arise in Texas.

To address water quality of these systems, we anticipate the need to include modeling of the following *additional* watercourse environments:

(1) the contributing catchment, including soil and vegetation, and the effect of different surface properties,
(2) tributaries and small drainageways

(3) elements of the root zone or vadose zone in the watershed
(4) small reservoirs for erosion-control or agricultural water-supply purposes

While degraded water quality or limits on use of regulatory concern will probably not arise often (or at all) with these systems, they do have a potential impact on the watercourses listed above and would need to be included in the TMDL model. The single most important of these is the contributing catchment, which for most Texas watercourses represents the primary source of nonpoint pollution.

Finally, a TMDL determination also has an implicit time scales that must be accommodated by the selected model. A differentiation must be made between the time scale of the problem context and the time resolution in a model. Water quality management problems can entail any of the following time scales:

(1) sudden excursions in water quality due to short-term rise and recession of flood hydrographs
(2) sudden excursions in water quality as in (1) separated by periods of steady or slowly varying flows
(3) longer term, slower variation in water quality due to seasonal or longer term variation in hydroclimatology and associated wasteloads
(4) equilibrium (steady-state) water quality under critical external conditions

A problem motivating the context of (1) is one in which contaminants are flushed into the watercourse by storm runoff, or are mobilized from the bed by the higher stream velocities resulting from storm flows. A dramatic example is the notorious "Black Rise" on the Upper Trinity River. If the watercourse exhibits degraded quality both as short-term storm responses and during the periods of lower flows between such events, a time scale context of (2) may be necessary. Another problem context in which this time scale of variation is required is when the objective is to determine a long-term average response to a variety of storm and nonstorm events. Agricultural land management often necessitates this problem context.

The problem context entailing time scale (3) is similar except that the specific short-term responses to storm events are not central to the occurrence of degraded water quality, so the fine details of storm hydrographs and the water-quality response are not needed. An example would be contaminants stored in the watercourse by runoff events that influence water quality long after the storm hydrograph has receded. Another example would be determining the effects of long-term variation in wasteloadings or hydroclimatology. In this case, the integrated loads from storm events are needed but not their fine time detail. Yet another special case would be the seasonal variation in a waterbody, such as seasonal freshets in a river, or summer stratification in a lake.

The last time scale (4) results when time variations in loadings, hydrology and water quality response are not material to the management problem. This is the problem context for a point-source assimilative-capacity determination in which the critical conditions are usually summer low flows.

In order for a model to be capable of depicting one of these time scales, it must have an appropriate time resolution in the model operation (including inputs), and must have process formulation that are suitable for that time resolution. One index to the time resolution of a model is the smallest time step the model can accommodate (or for which adequate validation has been accomplished). Whether the processes are properly formulated for a given time scale is a more subtle matter, discussed further in Ward and Benaman (1999). For the present context we differentiate four types of model time resolution:

- storm event
- continuous time
- slowly varying
- steady state

Storm event models are designed to depict the highly variable, immediate response of a storm hydrograph. A *continuous time* model includes this storm-response capability but also treats the very different hydrological behavior during the interstorm periods, when the watershed is desiccated by evapotranspiration and infiltration, and interflow plays a greater relative role in producing streamflow. "Continuous time" is an unfortunate choice of terminology, because these models are discretized in time, but this is the common patois among modelers. *Slowly varying* models have an integration timestep that is long in comparison to storm hydrographs, and storm loadings, if included in the model at all, are integrated over the model time step. *Steady state* models usually involve a model equation in which the time derivative is assumed *ab initio* to be zero, but there are a few steady-state models that use time as an asymptotic parameter, integrating forward until the solution equilibrates. (In fact, a time varying model can be used to determine the steady state response by this tactic.) A reliable indicator of whether a model is steady-state is whether time variation is allowed in any of the external input parameters.

A list of the models reviewed in this study and the extent to which they would appear to be of potential value in the Texas TMDL process are summarized in Table 4-1. Those models that are recommended for consideration for use are shown in boldface italics in this table. Where a model has been eliminated from recommendation, the principal reason(s) for this is given in the last column. The most common reasons proved to be (1) an inadequate history of usage, as reflected in the technical literature, (2) insufficient demonstrated application to watercourses typical of Texas environments, which includes the extent of field verification that the model has received, and (3) constraints on access to the model, either because it is proprietary or that it is "in development" or limited to "research use." For those models that survived the screening process and are therefore listed for consideration, Table 4-1 lists problems that may hamper use of the model in a TMDL context, e.g., the model is steady-state only, there is no hydrodynamic or no water quality capability, or the model code may be difficult to apply.

Table 4-2 categorizes the most likely modeling requirements for Texas TMDL's according to watercourse type and model time resolution, showing how the models recommended for consideration (Table 4-1) meet the requirements of the State. Those combinations of watercourse type and time resolution that are unlikely to be needed for TMDL's are indicated by gray cells in this table. One immediate observation to be made about Table 4-2 is that there are several places in the table, representing combinations of time resolution and watercourse type, for which there does not exist a suitable model. Even for those combinations for which there are

Table 4-1

Summary of model assessments
Models in boldface italics recommended for consideration

model	*watercourse application*	*screened to Level:*	*remarks*
ADAPT	watershed (field)	1	research model, limited history
AGNPS	watershed	1	insufficient currency
ANSWERS	watershed	3	event model, dated code
ANSWERS-2000	watershed	1	under development
BATHTUB	reservoirs	1	statistical, limited history
CE-QUAL-ICM	streams, lakes, estuaries	1	insufficient application
CE-QUAL-RIV1	streams & rivers	1	insufficient application
CE-QUAL-W2	reservoirs & deep dendritic estuaries	4	application difficult, code may contain bugs
CHARIMA	rivers & estuaries	1	not in public domain, limited history
CLAWS	watershed, streams & rivers	1	under development, poorly documented
CREAMS	agricultural fields	1	not adaptable to watersheds
DESERT	watershed, streams & rivers	1	under development, poorly documented
DR3M	watersheds	1	urban runoff, limited history
DYNHYD	surface waterbodies	3	link-node 1-D, dated code
DYNTOX	surface waterbodies	1	insufficient documentation, limited history
EFDC	estuaries & bays	4	complex to use, insufficient history of application, inadequate acceptance
EPIC	agricultural fields	1	not adaptable to watersheds
EUTROMOD	lakes	1	dated, limited history, inadequate acceptance
EXAMS	reservoirs & lakes	1	insufficient application
GLEAMS	farm-scale catchment root zone	2	not adaptable to watersheds, but may have limited utility in manure or litter application BMP evaluation
GWLF	watersheds	1	inadequate documentation, limited history
HSPF	watersheds, streams & rivers, small reservoirs	3	process models poorly documented, difficult to apply

(continued)

Table 4-1
(continued)

model	*watercourse application*	*screened to Level:*	*remarks*
IDOR^{2D}	lakes, reservoirs, estuaries	1	proprietary
IIHR	watershed	1	no longer supported, limited history
MIKE-SHE	watersheds, streams & rivers, vadose zone & aquifers	1	proprietary
MODFLOW	vadose zone & aquifers	1	not adaptable to watersheds
PHOSMOD	lakes & reservoirs	1	not current, insufficient application
POM	lakes, estuaries, bays	4	complex to operate, limited water-quality capability
PRMS	watersheds & vadose zone	3	input demands less than HSPF, limited water-quality capability, GUI input management system under development
QUAL2E	rivers, 1-D estuaries, main-stem reservoirs	3	limited to steady-state conditions
QUALTX	rivers, 1-D estuaries, main-stem reservoirs	3	limited to steady-state conditions, specific to Texas watercourses
RIVER3	rivers	1	insufficient application, inappropriate for Texas hydrology
RIVMOD	rivers & streams	1	hydraulics only, limited history
RUSLE	agricultural fields	1	limited applicability, statistical model, sediment load only
SLAMM	urban watersheds	1	inappropriate for Texas, limited history
SMPTOX	rivers & streams	1	not suitable for TMDL-type problem, in appropriate for Texas hydrology, not current, limited history
SPUR	watersheds	1	under development
SWAT	watersheds, lakes vadose zone	3	lumped formulation, statistical process models
SWIM	watersheds	1	under development

(continued)

Table 4-1
(continued)

model	*watercourse application*	*screened to Level:*	*remarks*
SWMM	watersheds	3	emphasis on urban catchments
SWRRB	agricultural fields	1	replaced by SWAT
TxBLEND	bays & estuaries	4	no water-quality capability, limited technical acceptance
WAM	watersheds, streams & rivers	1	proprietary
WASH123D	watersheds, vadose zone & aquifers, rivers & streams	1	difficult to use, insufficient history of application, inadequate acceptance
WASP	surface waterbodies	3	must be coupled with suitable hydro-dynamic/transport model
WEPP	agricultural fields & root zone	1	not readily applicable to Texas sheds, insufficient application
WMS	watersheds	1	proprietary, interface "shell"

Table 4-2

Texas TMDL modeling requirements by watercourse type and time resolution
and models satisfying requirements.
Combinations not expected to be widely necessary are filled in gray

	TIME RESOLUTION			
WATERCOURSE TYPE	*steady state*	*slow time variation*	*continuous time variation*	*storm event*
field or lumped catchment	GLEAMS		SWAT	ANSWERS, SWAT*
watershed		HSPF, SWAT, PRSM	HSPF, SWAT, PRSM	HSPF, PRSM, SWMM, ANSWERS
stream/river	QUALTX	DYNHYD/ WASP		
reservoir, unstratified	QUALTX	DYNHYD/ WASP		
reservoir, stratified		CE-QUAL-W2		
estuary reach, longitudinal	QUALTX	DYNHYD/ WASP		
estuary reach, stratified	CE-QUAL-W2	CE-QUAL-W2		
coastal embayment, vertically averaged			TXBLEND, POM, EFDC	
coastal embayment, 3-dimensional			POM, EFDC	

*average conditions over long simulation period one or several models, there are other problems. ANSWERS and DYNHYD are old models whose formulations could be substantially improved. As discussed in Ward and Benaman (1999), models can be decomposed into "compartments" treating hydraulics (i.e., hydrodynamics), transport, waterborne parameter kinetics, and sediment mobilization and transport. Almost every one of the models shown in Table 4-2 lack one or more of these compartments, which will hamper that model's utility in a TMDL determination. Even for those that do include all of these compartments, some of the process formulations are inadequate. SWAT, for example, relies upon the SCS curve number method for its runoff hydrology and the Universal Soil Loss Equation for sediment loading, see Ward and Benaman (1999). This is why the developers of SWAT caution that it should be used to determine long-term average loadings from a watershed, and may not perform well for individual storm events (Dugas, pers. comm., 1999)

The lack of availability of suitable reservoir water quality models is particularly problematic. CE-QUAL-W2 is difficult to apply, does not have sufficient simplified default parameters as an alternative to its overparameterized input requirements, and may contain programming bugs. For some shallow reservoirs QUALTX may work, but this is pressing the range of applicability of this type of model. A model formulated along the lines of BATHTUB, but with less reliance on statistical nutrient responses, would be especially useful. Another significant lack evidenced by Table 4-2 is a receiving stream model capable of treating the dynamic response of water quality to a storm event. (HSPF, we note, includes a receiving stream submodel, but there is no hydraulic capability, and, moreover, it is a very poor model for water-quality management because of the limited spatial resolution, see Ward and Benaman, 1999.)

The principal conclusions emerging from this review are as follows:

(1) Although there are many watercourse models on the market, there is no one model suitable for all (or even the majority) of TMDL projects anticipated in Texas. Even for specific combinations of watercourse characteristics and problem time scale, the existing models may not be entirely adequate to the problem. For some combinations, there do not exist suitable models.

(2) For watersheds, the most appropriate extant models are HSPF, PRMS and SWAT. Each of these, however, has significant weaknesses and limitations for Texas environments. Many of the process terms in these models may require additional study, validation or re-formulation for application to TMDL's (see Ward and Benaman, 1999). Between HSPF and SWAT, the deterministic basis of HSPF hydrology and sediment loading is preferable to the empirical basis of SWAT, which employs the SCS curve number and the USLE. PRMS appears to have a better formulation of both hydrology and sediment mechanics but lacks application experience in systems typical of Texas. The fact that both HSPF and PRMS use the same file management front end is a major convenience.

(3) For streams and rivers, the most appropriate extant models are QUALTX for the steady-state, low-flow-dominated problems, and the DYNHYD/WASP combination for time varying problems. The hydraulic basis and computational strategy of DYNHYD are dated. There is not extant a truly suitable model for the short-time response of a storm hydrograph.

(4) For lakes and reservoirs, QUALTX or DYNHYD/WASP may be suitable if the reservoir behaves more like a continuously stirred tank reactor (CSTR), i.e. hydrodynamic transport processes do not result in substantial spatial gradients. This will probably be true for smaller, shallow reservoirs. For those that are deeper, subject to high internal circulations (notably due to power plant operations), or evidence important vertical stratification in water quality, these models will not be suitable. The only proven, but rather undesirable, option at this point is CE-QUAL-W2.

(5) For one-dimensional estuaries, i.e. tidal or salt-intrusion reaches of a river, there is no suitable model for short time-resolution problems: in this type of system, intratidal variation can be as problematic as storm event response. For management problems amenable to longer time-scale averaging, *viz.* intertidal, QUALTX or DYNHYD/WASP may be appropriate. Validation studies will be necessary, and high dispersion coefficients (e.g., Ward and Montague, 1996) will probably be necessary.

(6) For the large, open, spatially complex system of a coastal embayment, there are three models considered in this review with capabilities for addressing this sort of system: EFDC, POM and TXBLEND. Each might be suitable, but each would require additional development work and field testing to be useful. (However, it is unlikely that many TMDL problems in Texas will require modeling these complex system.)

The following recommendations to TNRCC are proffered:

(1) Selection of a model for a Texas TMDL determination should be first based upon the type(s) of watercourse involved and the time scale dictated by the water-quality problem(s) of that watercourse. Selection should be further based upon the adequacy of the processes represented in the model (discussed in more detail in Ward and Benaman, 1999). Availability of a model code that includes a (perhaps purportedly) user-friendly interface should not *per se* be a criterion of adoption.

(2) As this project did not include actual operation of the models reviewed, we recommend that the models deemed candidates for consideration (Table 4-1) be subjected to operational testing and evaluation. In some cases, these models are being used in TMDL projects underway in Texas, in which case the modeling task should be expanded to include validation and evaluation of the model. Operation and comparison of two or more candidate models to the same watercourse evaluation can be especially useful.

(3) It has been many years since TNRCC (and its predecessor agencies) has carried out substantial projects in model development. From an early role of a national bellwether in developing and applying the "new" technologies of modeling and rigorous field monitoring to water quality management, the State has retrenched to a reliance on off-the-shelf software, or its venerable fallback QUALTX. The requirements for TMDL determinations in the State will necessitate at least major adaptations and modifications to the candidate models listed here, and in some cases new models. We recommend that TNRCC initiate a project of model development and validation addressing the specific features of Texas watercourses and hydroclimatology to meet this need.

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